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DESIGNING FOR MUSCULAR STRENGTH OF VARIOUS POPULATIONS

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Hand- and foot-operated controls are the input devices through which the operator effects the performance of manned systems. Selection of the type of control and its location within the reach envelope depend, to a large degree, on biomechanical parameters of all user populations, i.e., mainly on their body dimensions and on their strength characteristics, including motion stereotypes and lateral preferences. Muscular strength for control operation can vary significantly with age, sex, cultural origin, health,

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training, motivation, and other specific traits of the operator population. This paper discusses several of these variables and their biomechanical implications, and describes techniques and a regimen to design new equipment or modify existing equipment to conform to the strength characteristics of the operator populations.

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FOREWORD

This study was conducted under Project 7184, "Human Engineering in Advanced Systems," Task 718408, "Physical Anthropological Criteria for Air Force Systems Design," Work Unit 71840807, "Biomechanic System Design," by members of the Anthropology Branch, Human Engineering Division, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

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INTRODUCTION

The ability to exert muscular strength characterizes, like other anthropometric descriptors, an individual as well as a population. Information on strength is important to the ergonomist[1] who designs a new man-operated system or evaluates existing equipment. Simple machinery, and of course hand tools, generally pose rather high demands on the strength of the user. However, even sophisticated manned systems are controlled by hand- or foot-operated controls. Some of those controls require very little energy input, but many tax the operator's strength thoroughly. Critical controls, especially for emergency operation, are often laid out for application of large force or torque. For normal operation, the Human Factors engineer selects an "optimal" value within the continuum of strength of the prospective user populations.

Type of the control selected, its arrangement, mode of operation, and the control dynamics to be implemented depend, to a large degree, on body dimensions, handedness, motion stereotypes, and especially on muscular capabilities of the user population. These characteristics can vary significantly with sex, age, profession, cultural and civilizatory status, and area of origin (nationality) of the population.

STRENGTH IS SPECIFIC

It has been shown in many experiments that strength is highly specific.[2] The specificity applies to several aspects:

- Different definitions, terminologies, procedures, and interpretations have led, in the past, to different "strengths." Attempts have been made to eliminate the ambiguities and to standardize the assessment of strength.[2]

- Strength describes the ability to exert force or torque to a given instrument (or control) at a given location, in a given direction. Different strength scores, even when exerted by the same subject, are often not highly correlated.

- Strength depends not only on the muscular capability, but also on health and training, technique and experience, motivation and body position.

Critically using the available information, the ergonomist must decide whether existing strengths are pertinent to his design project (Chapanis, 1967), specifically, whether the strength test conditions resemble the design strength requirements sufficiently, and whether the test population sample can be considered representative of his prospective user population.

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[1] *Ergonomics and Human Factors Engineering use somewhat different approaches (Chapanis, 1970) but are very similar in their basic philosophies: Researching man, describing man, fitting task and equipment to man (Kroemer, 1970b). In this sense, both terms are used in this text without discrimination.*

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[2] *See appendix.*

DESIGN FOR STRENGTH IS SPECIFIC

Every tool, device, equipment, or man-controlled system has its very own purpose(s), and must be designed to fulfill specific requirements. With respect to operator strength requirements, tools have to be grasped and manipulated, equipment has to be pushed or pulled or lifted, controls[3] must be operated in prescribed ways, must be rotated, pressed and moved within given guadrants of the workspace to achieve the special purpose.

Previously, the designer often started from the overall task of the system, equipment, or tool, and considered the human operator only after the "working side" of the machinery had been established. In this manner, machine tools, the power plant and the chassis of an automobile, the performance requirements of an airplane were habitually determined first. Only then, within the tight constrictions posed by the design already laid out, attempts were made to take characteristics of the human operator into account. Very little choice was left, e.g., as to what type of control to select, where to place and how to operate it.

Human-oriented design starts by considering specific capacities of the operator and improves, boosts or modifies these characteristics through special devices. This method was in effect during the "natural" development of most hand tools. (It is fascinating to speculate what could be achieved if the engineer would start systematically with the operator, enhance his characteristics and only then evaluate what the strengthened operator is able to do).

In practice, the capabilities of the operator and the requirements posed by the task must be matched to each other in the first stage of the design process. Such careful adaptation has become increasingly necessary with increasing complexity of man-operated systems such as airplanes, spacecraft, etc., and with growing reluctance of the worker to tolerate inadequate working conditions.

This paper discusses the practical application of information on muscular strength, laterality, and stereotypical pattern of various populations. In particular, this paper refers to the operational importance of the magnitude of strength critical for control layout (section II), the various types of strengths required in control operation (section III), and the dependency of strength on the control location (section IV). In section V, these separate aspects are combined and discussed with respect to their specific effects on the design of tools and equipment, and a regimen is described used by the designer to adapt the product to population strength characteristics.

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[3] *In this paper the term "control" connotes any device serving to transmit muscular strength to the equipment.*

SECTION II

MAGNITUDE OF STRENGTH CRITICAL FOR EQUIPMENT LAYOUT

In control layout, the force/torque requirements must be carefully adapted to the operator's strength available under *operational* conditions. Operator strength is critical in setting either a minimum value for control manipulation, so that even weak operators can actuate the control, or in setting a maximum value, preventing the system from being inadvertently actuated, or damaged. Between the minimum and the maximum requirements is a "grey area" excluding (or including) certain portions of the user population.

The equipment requirement varies with the frequency and duration of operation, and can depend on environmental conditions (e.g., acceleration). A given operator's strength, in turn, depends on his muscular capabilities (which are subject to change depending on health, training, exhaustion, etc.) as well as on his skill in exerting his inherent capability, on the body support (reaction force) available to him, and on many other biomechanical and psychological variables.

A number of case reports may accentuate the problems encountered when designing for strength.

Case 1

Cathcart, Hughes and Chalmers (1935) reported an average force of 363 lb exerted by approximately 10,000 British workers in isometrically pulling upward with both hands at a horizontal bar located at mid-thigh height. Using the same backlift action at a similarly located horizontal bar, 900 USAF cadets exerted a mean upward force of 520 lb, as reported by Clarke (1945).

The author thoroughly examined both original reports. No obvious differences in experimental design, in experimental equipment, in measuring and recording techniques, or in statistical data treatment could be discerned from the texts which might explain the discrepancies in the strength scores. If we accept as a fact that the cadets were indeed stronger, were they really about ⅓ stronger than the workers? Similar questions arise when trying to match strength scores stemming either from different populations, or resulting from surveys conducted by different researchers possibly employing different techniques.

Case 2

Forces exerted upon a rigid pedal with the preferred foot by attempted (isometric) extension of the leg, with the operator sitting and supported by a backrest, were measured by several researchers under a variety of experimental conditions (see Kroemer, 1971, for a compilation). Table 1 lists the largest average forces reports in each study. Large unexplained differences are obvious.

Using the number of subjects to weight the average forces, overall mean strengths were computed for each national subject population. While the U.S. and the British males average almost the same values (2690 versus 2750 Newton), the German male subjects exerted only about half as much leg thrust (1520 N). If the experimental procedures used are indeed

Table 1. Mean Maximal Leg Strength Reported for US, British and German Populations

Average Force in Newton	SD	Subjects	Source
1860	no data	2 US pilots	Gough & Beard 1936
2520	440	515 US pilots	Elbel 1949
3230 (median)	no data	166 US tank personnel	Martin & Johnson 1952
Weighted mean: 2690	-	683 US males	-
3770	no data	6 Englishmen, "powerfully built"	Hugh-Jones 1947
3080	no data	32 British soldiers	Hugh-Jones 1947
3070	no data	16 British teen-agers	Hugh-Jones 1947
1710	no data	20 British students	Rees & Graham 1966
2535	no data	5 British pilots	Crawford 1954
Weighted mean: 2750	-	79 British males	-
2160	180	11 German pilots & engineers	Hertel 1930
1402	300	60 German men	Rohmert 1966
Weighted mean: 1520	-	71 German males	-
1510	no data	2 German women	Müller 1936
1010	no data	10 German women	Rohmert & Jenik 1972
Weighted mean: 1100	-	12 German females	-

comparable, this indicates a distinct difference in exertable leg strength which must be taken into account by the designers. However, there are no anthropometric or biomechanical indicators which would make such a discrepancy plausible. Hence, the difference in strength scores is likely to be an artifact of different experimental procedures.

Case 3

A number of researchers (Asmussen and Heeboll-Nielsen, 1961; Cathcart, 1927; Cathcart, Hughes and Chalmers, 1935; Hettinger, 1968; Hettinger and Hollmann, 1969) compared strength scores of men and women and found that women have approximately ⅔ the strength of men. Rohmert and Jenik (1971) reported forces and torques exerted with the hand or foot by a sample of women, and compared their scores with the strength data measured previously on a sample of men. The techniques used were the same in both studies. In torques about the long axis of the forearm (supination and pronation), the women exerted the classic ⅔ of the men's strength: However, the ratio varied between 0.52 and 0.91, with two ratios (considered irregular by the authors) larger than unity.

The ratios of leg forces exerted statically on a pedal were about 0.55 if the pedal was at the 95th percentile reach, and about 0.80 with the pedal at the 90th percentile reach contour but fell with closer pedal arrangements: the mean ratio again was about ⅔.

At the more distant pedal, such a large force could be applied because of the "toggle effect" brought about by wedging the almost extended leg between the opposing surfaces of seat back and pedal. Such biomechanical conditions bringing about very large forces were also observed earlier in a number of experiments. For example, Kroemer (1969a) reported such effects in push forces exerted with the hands and feet; Hugh-Jones (1947) found that in certain pedal arrangements, "London School Boys" could exert about as much thrust as soldiers or his primary "powerfully built" male subject.

Which then is the "strength" the designer has to take into account: The "regular" muscular capacity which is not a true maximum in the sense that under no conditions one could exert more, or the maximal "position force" brought about by exceptionally advantageous biomechanical conditions? The answer lies in the intended application of the data: The truly maximal force is of concern if overstressing of the control system must be considered; the "regular" strength will apply if "regular" operational conditions prevail.

Case 4

Guthrie, Brislin and Sinaiko (1970) report on grip strength measurements taken on an Asian and a U.S. male population. Eighty-two Vietnamese young men were found to be considerably weaker than a sample from the U.S.A.: Their 75th percentile grip strength compared to the 25th percentile score of the western sample.

In this case, comparable population samples are subjected to the same test by the same researcher in order to assess their respective strength capabilities. These are the kind of data that the designer needs to adapt the equipment characteristics to the user populations.

Unfortunately, such directly comparable data, taken systematically in large scale for a number of applications, are still scarcely found in the literature.

Case 5

One hundred and nineteen lb were found to be the mean "maximal" weight of boxes 26 x 11 x 7 in., to be lifted with both hands 3 ft from the floor (Emanual et al., 1956). Seventy-one to ninty-six lb were reported as mean "reasonable" weights of 12 x 12 x 6 in. boxes, to be lifted with two hands 3½ ft from the floor (Switzer, 1962). Based on their experimental findings as well as on a literature survey, Snook et al., (1970) concluded that 50 lb are the maximum "permissible" weight to be lifted by unselected adult U.S. male workers.

This example shows that values pertaining to maximal, tolerable, acceptable, reasonable, comfortable, desirable etc. efforts vary widely, depending on the work requirements, and on criteria applied to find the "optimum" for each given case. They also vary considerably among different populations. Using the assumption that the load to be carried by a soldier should not exceed ⅓ of his body weight (White 1964a, b; Hart, Rowland and Malina, 1967), equipment mass carried by Korean personnel should be limited to less than 20 kg and be about 18 kg for Thai and 17 kg for Vietnamese; whereas Americans could carry about 24 kg (Anthropology Branch, 1970).

The last examples illustrate that it is indeed very difficult to tie together recommendations for dynamic lifting of loads, and to compare the lift loads with data on static strength capabilities as reported in the literature and referred to in Case 1. Static strength scores are numerically much larger than the weights (mass forces) recommended for dynamic lifting or carrying, as discussed in detail elsewhere (Kroemer 1970a).

It is often assumed that a condition allowing maximal exertion of isometric forces is also optimal for other than static efforts. But, "maximum" is the greatest quantity possible, the upper limit of variation, while "optimum" is the best, the most favorable condition. Hence, these terms refer to two different phenomena. Optimum needs a further definition: optimum in what respect? With regard to muscular efforts, there are different optimal conditions; e.g., for static forces in contrast to dynamic work, for accurate movements in contrast to short outbursts of energy, etc. In human engineering, an "optimal" work condition often is one in which the operator undergoes as little physical strain and fatigue as possible, so that he can perform his task for a long time without deterioration.

Cases 1 through 5 illustrated the complexity of the problems encountered when trying to compare strength data from different sources, referring to different populations. The examples also showed the dispersion to be expected from strength data.

SECTION III

TYPES OF STRENGTHS REQUIRED FOR CONTROL OPERATION

Different "strengths" are required from the operator if he has to rotate or twist, to squeeze or press, or to push or pull fore or aft, left or right, up or down. Also, the type of control operation often interacts with control location and environmental conditions in determining magnitude, manner and direction of human strength exertion.

Static forces and torques applied by sitting or standing subjects depend decidedly on the body position during exertion. In many cases, force or torque capability is not limited by the muscular capacity but by the reaction force generated by body weight, body support, and body posture. A given spatial control-body arrangement may be rather inefficient in certain strength exertions but very suitable for another strength generation.

Rohmert (1966) together with Jenik (1971) provided information on hand torques exertable in attempted rotation of the arm about its long axis in the elbow or shoulder joint. These pronatory and supinatory torques were found not to be directly related to the magnitude of linear forces, also measured on the same subjects. Thordsen, Kroemer and Laubach (1972) assessed forces exertable to measuring devices located in typical aircraft control locations. They recorded not only the amount of force exerted in the requested direction, but also the forces applied, involuntarily and at the same time, in a plane perpendicular to the required direction. Figures 1 through 4 list the experimental results for one of the control locations ("Overhead" at 25.5 cm left and 120 cm above SRP)[1]. In this control position, a very large difference between strength scores was observed: While the mean backward force barely exceeded 80 Newton (figure 2), the upward efforts averaged almost tenfold this amount (figure 4). When the subjects tried to exert their maximal strength either forward (figure 1), backward (figure 2) or to the right (figure 3), they actually applied larger average forces orthogonally to these directions.

Both studies indicate that the type of control operation required must be carefully selected by the designer in order to match it to the strength exertable by the operator under the given conditions. The same control location may be extremely advantageous for torque exertion in a certain direction, but not suitable for certain linear force applications. Another aspect is that while a control is intended to be activated in a given way, the worker may actually operate it differently (even damage it) because he is involuntarily applying superior strength in another direction.

Recent research (Kroemer 1973) provided some quantitative information on the effects of increased gravitation on the strength available in several directions at controls in a number of different locations. Figures 5 through 8 illustrate some results. At $+5g_z$, for example, the subjects' ($n = 7$) ability to exert force to a control, located in front of the shoulder and grasped with the arm almost extended, was affected as follows: Backward strength (figure 5) was not changed significantly (two-tailed test, $p < 0.05$). Forward force capability (figure

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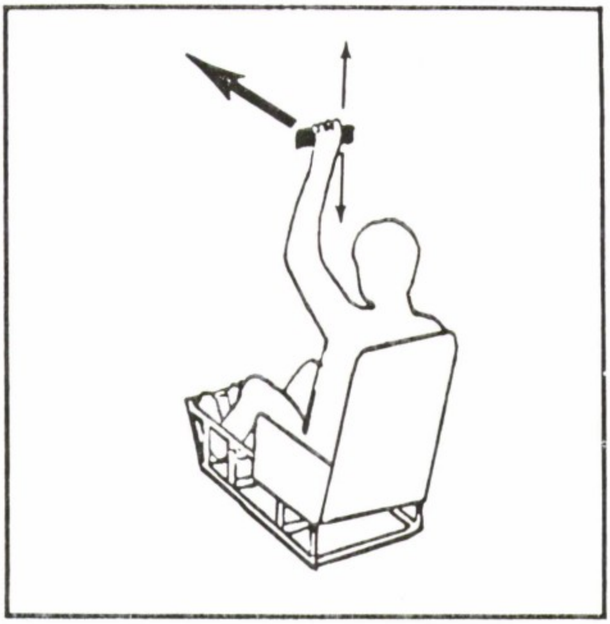
[1] *Seat Reference Point: The junction of seat pan and backrest planes in the symmetry plane of the seat.*

OVERHEAD CONTROL: FORWARD FORCE



THE SUMMARY STATISTICS

Newtons		*Pounds*
144.4	Mean	32.5
6.5	SE (Mean)	1.5
46.5	SD	10.5
4.6	SE (SD)	1.0
	Coef. of Var. (%)	32.2
	Symmetry-Veta I	0.9
	Kurtosis-Veta II	4.1
	Number of Subj. 51	

THE PERCENTILES

Newtons		*Pounds*
293.2	99th	65.9
230.4	95th	51.8
170.1	75th	38.2
139.4	50th	31.3
113.0	25th	25.4
78.7	5th	17.7
57.6	1st	12.9

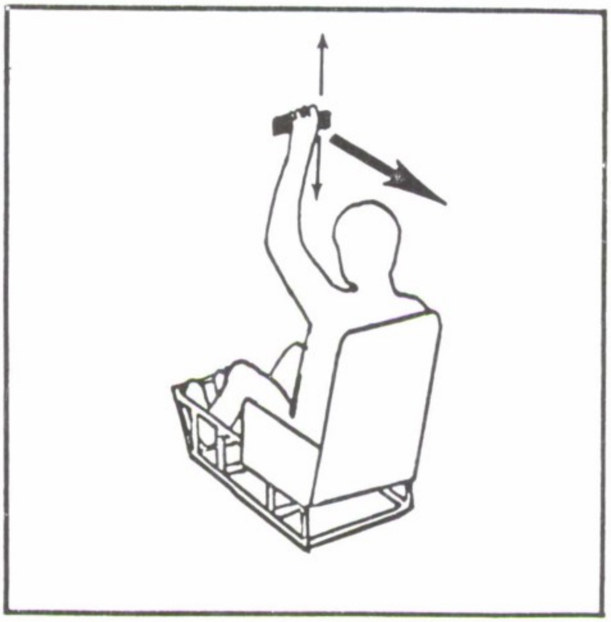
The handle assembly is located 10 inches left of SRP, 47.3 inches above SRP, and 0.0 inches forward of SRP. The handle is oriented in the horizontal frontal plane and the subject grasps it from the back. The subject is instructed to exert a force in a horizontal plane in the forward direction.

FORCE COMPONENTS RECORDED ORTHOGONALLY TO THE REQUESTED DIRECTION

	Mean *lb*	*SD* *lb*	*Maximum* *lb*	*Sample* *Size*
UP	32.1	25.1	121.0	26
DOWN	20.9	17.2	62.0	22

Figure 1. Overhead Control: Forward Exertion Requested.
(From Thordsen, Kroemer, and Laubach 1972)

OVERHEAD CONTROL: BACKWARD FORCE



THE SUMMARY STATISTICS

Newtons		*Pounds*
82.6	Mean	18.6
2.9	SE (Mean)	0.7
20.9	SD	4.7
2.1	SE (SD)	0.5
	Coef. of Var. (%)	25.3
	Symmetry-Veta I	0.9
	Kurtosis-Veta II	4.2
	Number of Subj. 51	

THE PERCENTILES

Newtons		*Pounds*
146.2	99th	32.9
120.2	95th	27.0
92.6	75th	20.8
79.3	50th	17.8
69.0	25th	15.5
54.5	5th	12.2
39.7	1st	8.9

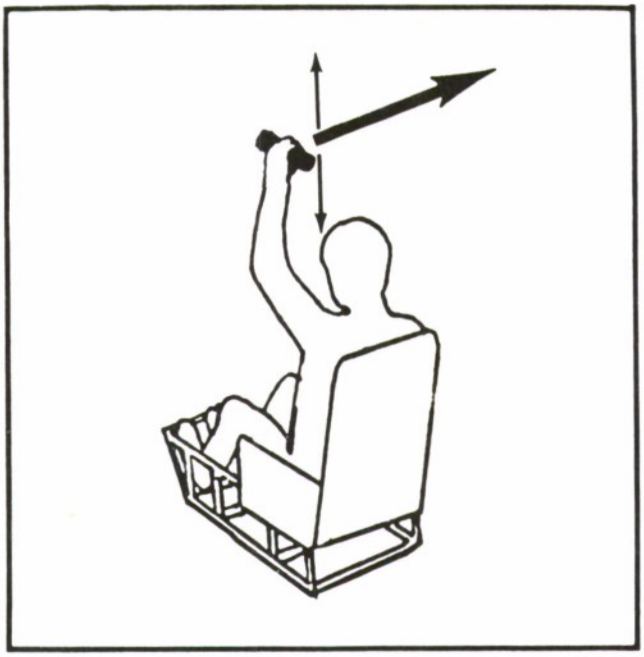
The handle assembly is located 10 inches left of SRP, 47.3 inches above SRP, and 0.0 inches forward of SRP. The handle is oriented in the horizontal frontal plane and the subject grasps it from the back. The subject is instructed to exert a force in a horizontal plane in the backward direction.

FORCE COMPONENTS RECORDED ORTHOGONALLY
TO THE REQUESTED DIRECTION

	Mean *lb*	*SD* *lb*	*Maximum* *lb*	*Sample* *Size*
UP	8.5	4.9	20.0	10
DOWN	21.7	18.0	78.0	39

Figure 2. Overhead Control: Backward Exertion Requested.
(From Thordsen, Kroemer, and Laubach 1972)

OVERHEAD CONTROL: RIGHT FORCE



THE SUMMARY STATISTICS

Newtons		*Pounds*
112.2	Mean	25.2
4.6	SE (Mean)	1.0
32.6	SD	7.3
3.2	SE (SD)	0.7
	Coef. of Var. (%)	29.1
	Symmetry-Veta I	0.2
	Kurtosis-Veta II	3.0
	Number of Subj. 51	

THE PERCENTILES

Newtons		*Pounds*
190.4	99th	42.8
172.9	95th	38.9
133.3	75th	29.9
108.6	50th	24.4
89.8	25th	20.2
64.7	5th	14.6
33.9	1st	7.6

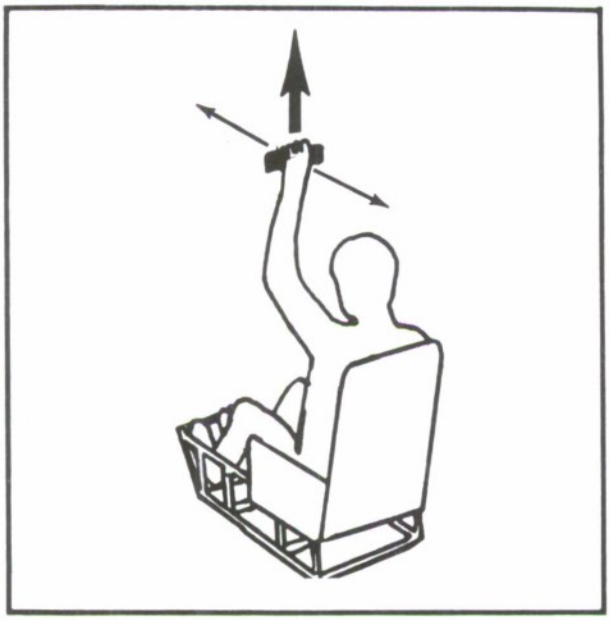
The handle assembly is located 10 inches left of SRP, 47.3 inches above SRP, and 0.0 inches forward of SRP. The handle is oriented in the horizontal sagittal plane and the subject grasps it from the left. The subject is instructed to exert a force in a horizontal plane in the right direction.

FORCE COMPONENTS RECORDED ORTHOGONALLY
TO THE REQUESTED DIRECTION

	Mean *lb*	*SD* *lb*	*Maximum* *lb*	*Sample* *Size*
UP	11.4	8.2	26.0	10
DOWN	33.5	20.7	88.0	38

Figure 3. Overhead Control: Exertion to the Right Requested.
(From Thordsen, Kroemer, and Laubach 1972)

OVERHEAD CONTROL: UP FORCE



THE SUMMARY STATISTICS

Newtons		*Pounds*
780.9	Mean	175.5
33.7	SE (Mean)	7.6
240.6	SD	54.1
23.8	SE (SD)	5.4
	Coef. of Var. (%)	30.8
	Symmetry-Veta I	0.7
	Kurtosis-Veta II	3.2
	Number of Subj. 51	

THE PERCENTILES

Newtons		*Pounds*
1399.1	99th	314.4
1255.5	95th	282.1
923.6	75th	207.6
733.2	50th	164.8
610.3	25th	137.1
479.4	5th	107.7
282.8	1st	63.6

The handle assembly is located 10 inches left of SRP, 47.3 inches above SRP, and 0.0 inches forward of SRP. The handle is oriented in the horizontal frontal plane and the subject grasps it from the back. The subject is instructed to exert a force in a vertical plane in the up direction.

FORCE COMPONENTS RECORDED ORTHOGONALLY TO THE REQUESTED DIRECTION

	Mean lb	*SD lb*	*Maximum lb*	*Sample Size*
FORWARD	30.0	16.0	77.0	50
BACKWARD	21.0	—	21.0	1

Figure 4. Overhead Control: Upward Exertion Requested.
(From Thordsen, Kroemer, and Laubach 1972)

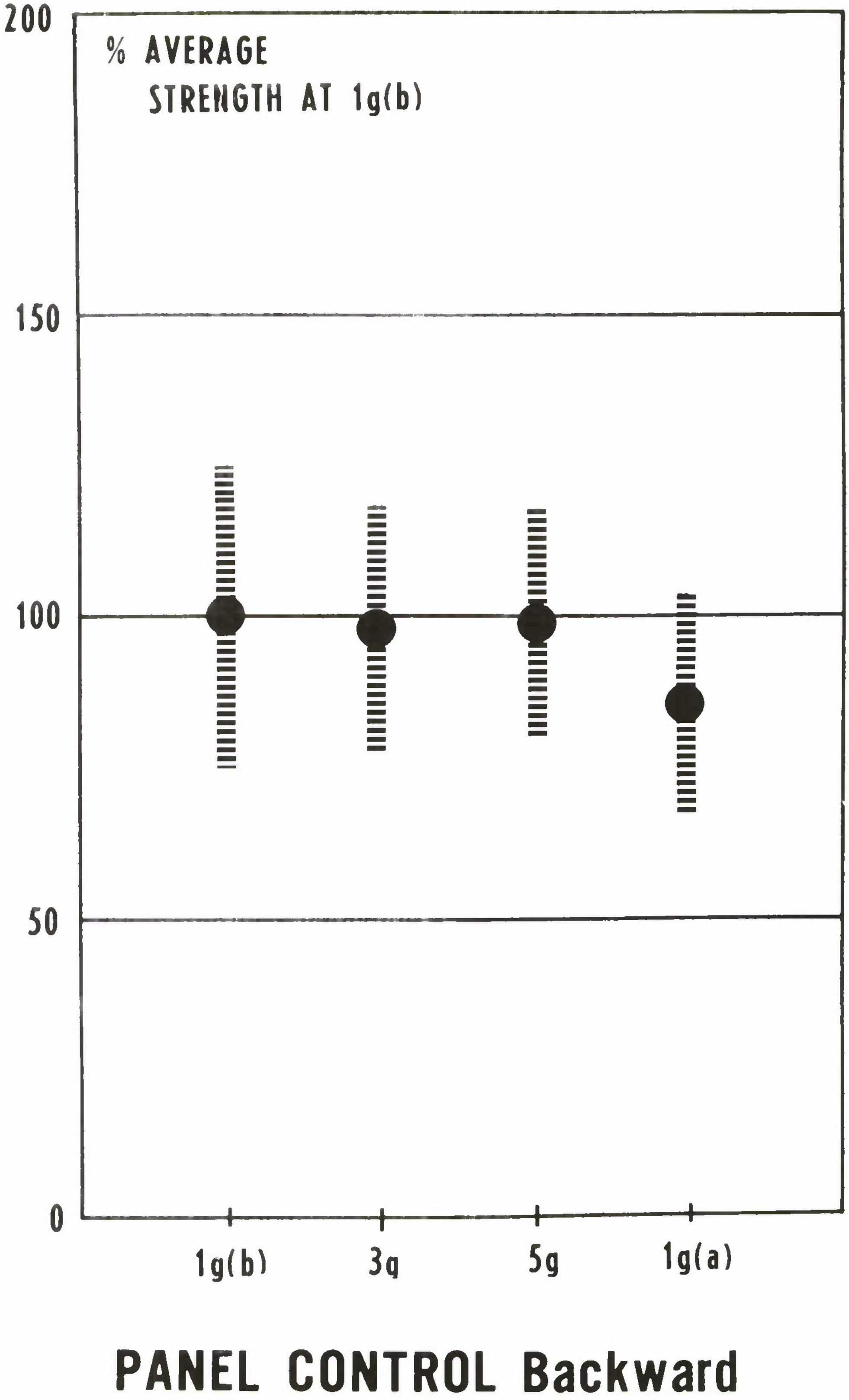


Figure 5. Panel Control: Backward Force at 1g (before), 3g, 5g, and 1g (after the trials).

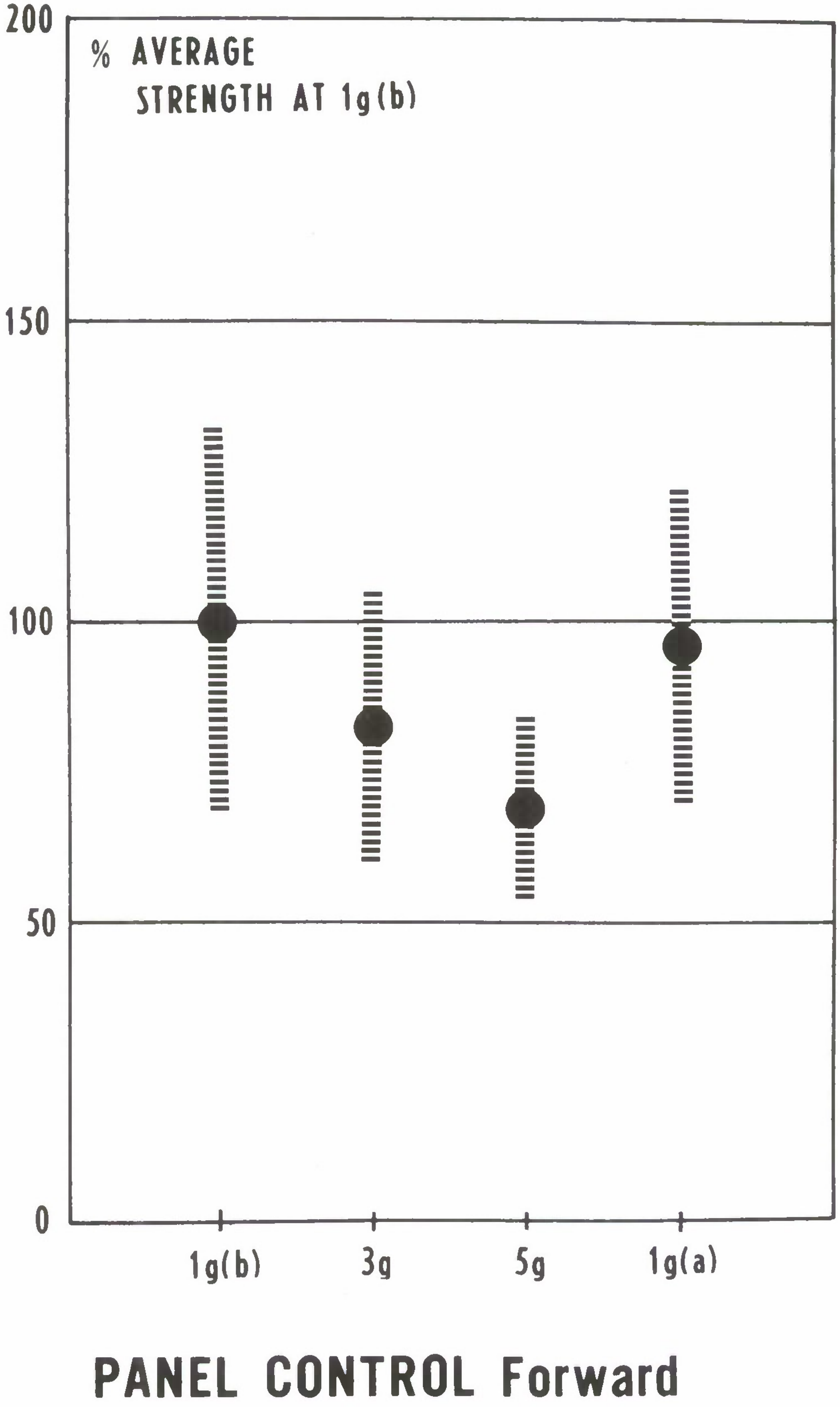


Figure 6. Panel Control: Forward Force at 1g (before), 3g, 5g, and 1g (after the trials).

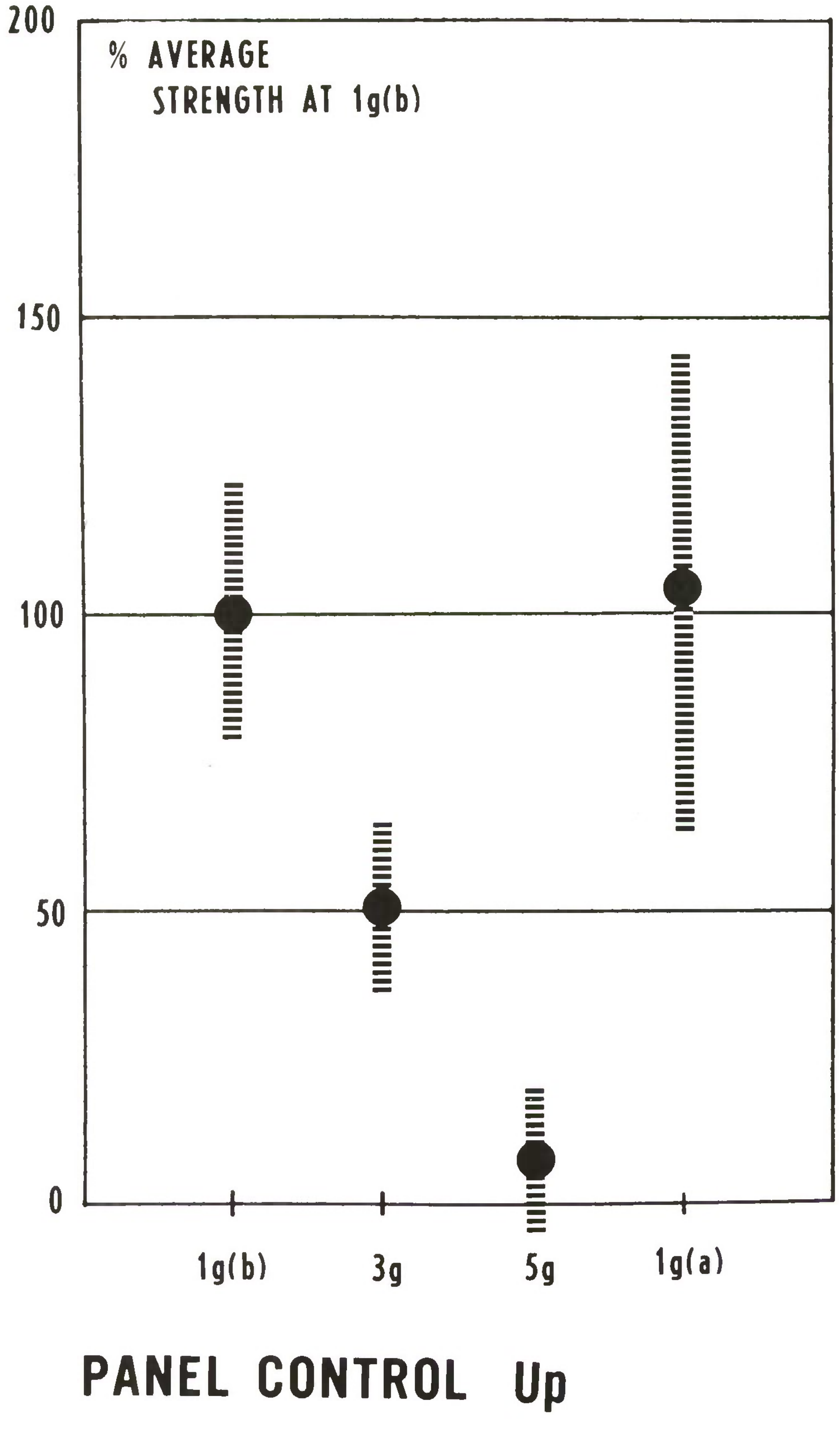


Figure 7. Panel Control: Upward Force at 1g (before), 3g, 5g, and 1g (after the trials).

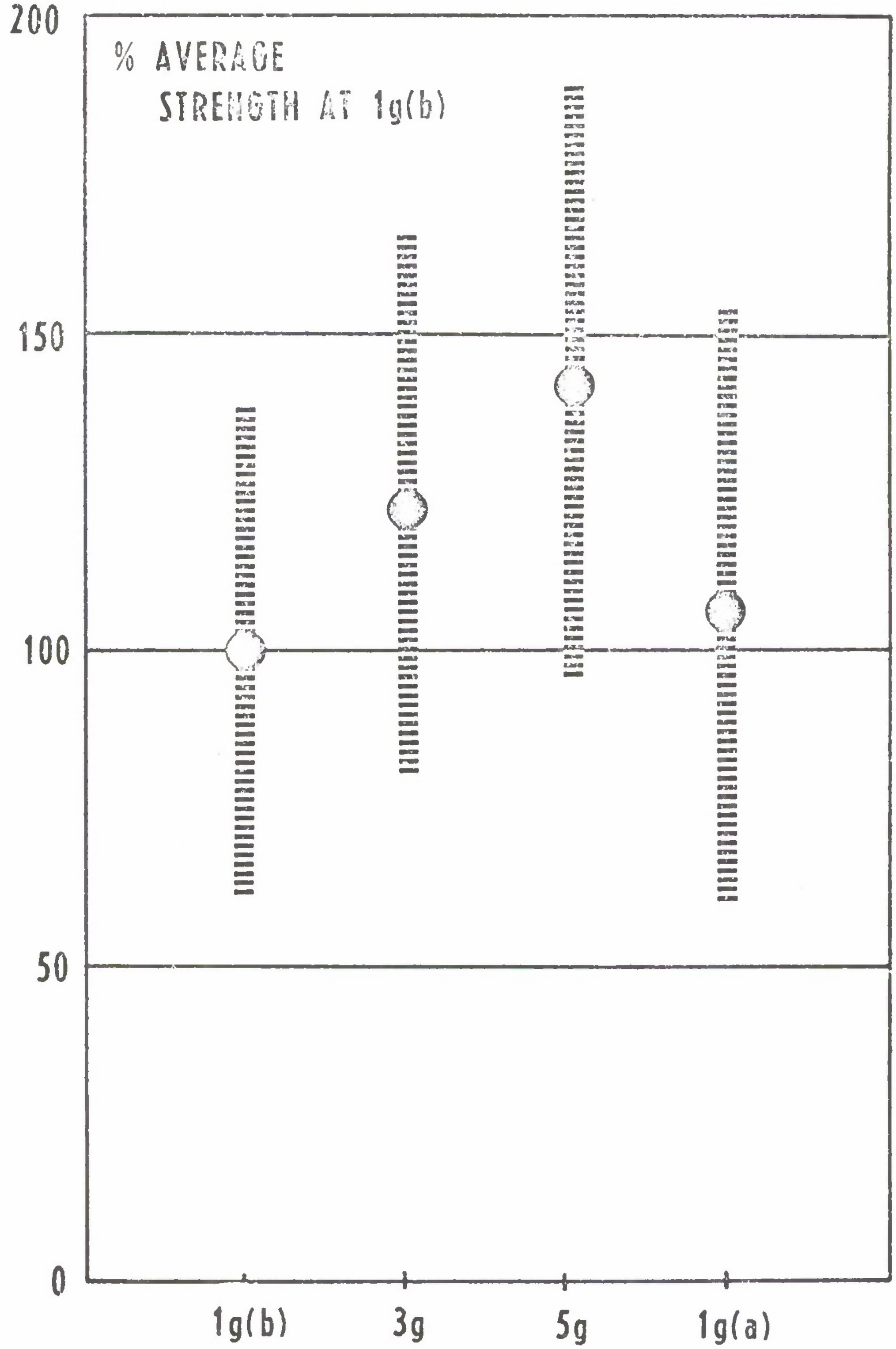


Figure 8. Panel Control: Downward Force at 1g (before), 3g, 5g, and 1g (after the trials).

6) was diminished by the environment. Upward force capability (figure 7) decreased dramatically from 100% at $+1g_z$ to about 50% at $+3g_z$ and fell to nil at $+5g_z$. In contrast, downward force (figure 8) increased about linearly with increasing g_z level.

These data emphasize that in selecting certain types (directions) of control operation, the designer must also consider environmental effects which may change the human strength capability drastically.

Case 6 is an example for a rather unexplored phenomenon: Stereotypically expected equipment responses to the operator's control actions. Certain control action/equipment response habit patterns exist consistently in certain populations: Automobile drivers, e.g., expect the vehicle to move to the right if they turn the steering wheel clockwise. Some such naturally expected relationships between control action and system response existing without special training or instructions, called population stereotypes, are listed in table 2.

Case 6

Table 2 lists standardized stereotypes relating four control actions with 5 equipment responses as established in the USA, in Great Britain, and in Germany (adapted from Morgan, Cook, Chapanis, and Lund, 1963; and from Kroemer, 1967, using DIN and ISO Industrial Standards).

It is remarkable that almost all stereotypes listed are found in each of the three countries. However, the "Control Up—Equipment Start" relationship does not apply in Great Britain, but is accepted in the USA and in Germany. The other exception is the "Control Clockwise—Equipment Up" relationship, which is not established in both Anglo-Saxon countries, but

Table 2. Stereotypes for Control Action - Equipment Responses in the USA, in Great Britain, and in Germany. (Morgan, Cook, Chapanis, and Lund, 1963; Kroemer, 1967)

CONTROL ACTION	EXPECTED EQUIPMENT RESPONSE				
	up	to the right	forward	clock-wise	start/ on/more
up	✓ USA ✓ GB ✓ G	Not USA Not GB Not G	?	Not USA Not GB Not G	✓ USA Not GB ✓ G
to the right	Not USA Not GB Not G	✓ USA ✓ GB ✓ G	Not USA Not GB Not G	?	✓ USA ✓ GB ✓ G
forward	?	Not USA Not GB Not G	✓ USA ✓ GB ✓ G	Not USA Not GB Not G	✓ USA ✓ GB ✓ G
clockwise	Not USA Not GB ✓ G	?	?	✓ USA ✓ GB ✓ G	✓ USA ✓ GB ✓ G

✓ established stereotype, recommended
Not not established, not recommended
? questionable or conditional

Table 2: *Stereotypes for Control Action—Equipment Responses in the USA, in Great Britain, and in Germany.* (Morgan, Cook, Chapanis, and Lund, 1963; Kroemer, 1967)

is accepted and recommended in Germany according to DIN 1410 for control operation and arrangement.

Case 6 shows that even between populations so closely related historically and culturally, definite differences in stereotypical patterns exist, which should be taken into account in the design of equipment to be used in each of the countries. Much more diversity must be expected in the stereotypes of less closely related countries; however, reliable information does not abound. It is open to speculation how many false operations of equipment imported from another country may occur daily and how many accidents may be attributable to mismatches of operator stereotypes and operational requirements. However, even within one highly developed nation spectacular examples of mismatches occur as described in Case 7.

Case 7

Aviation Week and Space Technology reported (20 Feb 1967, p. 16) that a prototype F111-A crashed when trying to land with the wings swept backwards instead of extended. At this time, the wing sweep control worked in a direction opposite to the wing motion. For later models, the handle linkage was changed to move in accordance with the motion of the wings.

Handedness, lateral preference, dexterity, laterality, dominance are terms connoting types and degrees of a subject's ability to perform common tasks better with either the left or the right hand (or foot) than with the other. However, the preference depends on the task to be performed: Different body segments may be used for, say, a finely controlled sensumotoric task, or for the exertion of brute strength (for a detailed discussion see, e.g., Barnsley and Rabinovitch, 1970; Palmer, 1967). Using mainly questionnaires, Annett (1970) distinguished several patterns of preferences, but they were neither discrete nor restricted to certain categories of tasks, but overlapped several categories.

Kimura and Vanderwolf (1970, p. 769) summarize the state of the art as follows: "... surprisingly little is known either about the nature of the motor skills involved in these (customarily executed) acts, or about the nature of the motor dominance described as hand preference." If indeed nature, definition, and assessment of laterality are still being debated, then this may explain why only such scant information on differences between various populations is available. At present, a rule of thumb is that less than 10 percent of any large national population are left-handed.

With respect to muscular strength, the evaluation of dexterity is relatively simple. The task of exerting a force to a measuring device is rather easily understood by most any subject, and he can usually determine (if necessary by trial) with which hand or foot he prefers to exert the force. If laterality is not ad hoc determined, it can be assessed comparing scores achieved with either hand separately. (This approach satisfies the desire to measure performance instead of stating preferences in order to determine laterality). Measures of grip strengths are exceptionally simple, since one just has to squeeze a grip (Hunsicker and Donnelly, 1955; Pangle and Garrett, 1966; Schmidt and Toews, 1970). Hence, assessment of grip strength could serve to determine one type of strength handedness in international surveys.

The operator's ability to exert pressure, force, torque, under all operational or emergency conditions, in combination with his stereotypical and laterality patterns, provides truly critical factors for the designer. Of these, muscular capabilities are structurally the same for all populations although they may be at different levels of magnitude according to training and health. However, stereotypical response and dexterity patterns may be fundamentally different between populations, and may be rather difficult to change. Also, complicated interactions must be expected between stereotypes, conditioned reflexes, handedness, muscular training and customary control operations of which we know (in a nonscientific way) mostly from personal experiences or anecdotical hearsay. Case 8 is a typical example of such information.

Case 8

A visitor from the USA rented an automobile in Japan. While driving in heavy traffic, requiring frequent gear shifting with the left hand, he found his left arm getting sore from the unusual exercise. Fatigued and unconsciously trying to avoid further strain, the visitor did not shift down in slowing traffic and stalled the engine when trying to accelerate rapidly in order not to be hit by another car. A serious accident resulted.

At present, no other choice is left to the designer of tools and equipment than to follow patterns established within certain industries or populations. In most countries, automobiles consistently have the gear shift on the right (but, as consistently, in some countries on the left). Single-seater airplanes usually have the throttle on the left. Sewing machines are commonly built "the wrong way," i.e., so designed that the left-handed person can operate them best. "Leaving it the way it was" perpetuates accepted designs and styles, and causes new products to conform to established procedures. It may also help to develop uniform strength patterns.

SECTION IV

STRENGTH IN RELATION TO CONTROL LOCATION WITHIN THE TOTAL REACH ENVELOPE

Locating a control adequately within the operator's reach envelope is one of the most critical features in design for human operation. The workspace available for shirtsleeve control operation has been described by Faulkner and Day (1970) and by Kennedy (1964). Encumbering equipment, or g-stresses can severely reduce the usable space. Overcrowding by too many controls can become a serious problem (Kennedy, 1972).

Figures 9 through 13 (from Kroemer, 1969b, 1971) serve several purposes. They indicate how human strength applications depend on the spatial relations between control and operator, and how the body support available to the subject affects the amount of force or torque he can develop. They also indicate a solution for the problem how to design for populations with different strengths. Figure 9 demonstrates that maximal leg strength can be applied to a fixed pedal if it is located at about seat height and so far forward that the leg must be almost fully extended to reach it with the foot. Other arrangements of the pedal within the reach envelope of the leg reduce the force capacity.

Although differences in strength exist between individuals, no gross morphological differences in skeletal or muscular structure prevail between different populations. Hence, the *relationships* between force or torque and relative location of the measuring device should not change appreciably between populations. The generality of biomechanical principles must hold as long as the relations between body dimensions, mechanical advantages, pull angles, etc., are the same. It has been shown that while the absolute forces exerted by men and women vary characteristically, the relationships between location, body position, and exerted strength are similar for both sexes.

Figure 10 depicts body angles and body support features necessary to describe biomechanical relationships during exertion of leg and foot strength. Figures 11, 12 and 13, using these descriptors, show the effects of changes in biomechanical variables on leg and foot strength. Similarly, Figure 14 schematically illustrates the torques exertable at different elbow angles. The magnitudes of elbow torques reported by about one dozen researchers vary considerably; the numerical differences probably reflect variations in experimental techniques and test conditions, as mentioned earlier. However, the trend of strength changing with the elbow angle is uniform.

The following case reports further illustrate the interactions between operator strength available at the control, and control location.

Case 9

Locating a pedal 100 cm directly in front of SRP allows approximately 95% of the male Central European population to operate this pedal with ease. However, for shorter legged populations (as many Asian populations, or European females) this distance is distinctly too large. For male Koreans, for example, this pedal location requires approximately 50% of all operators to

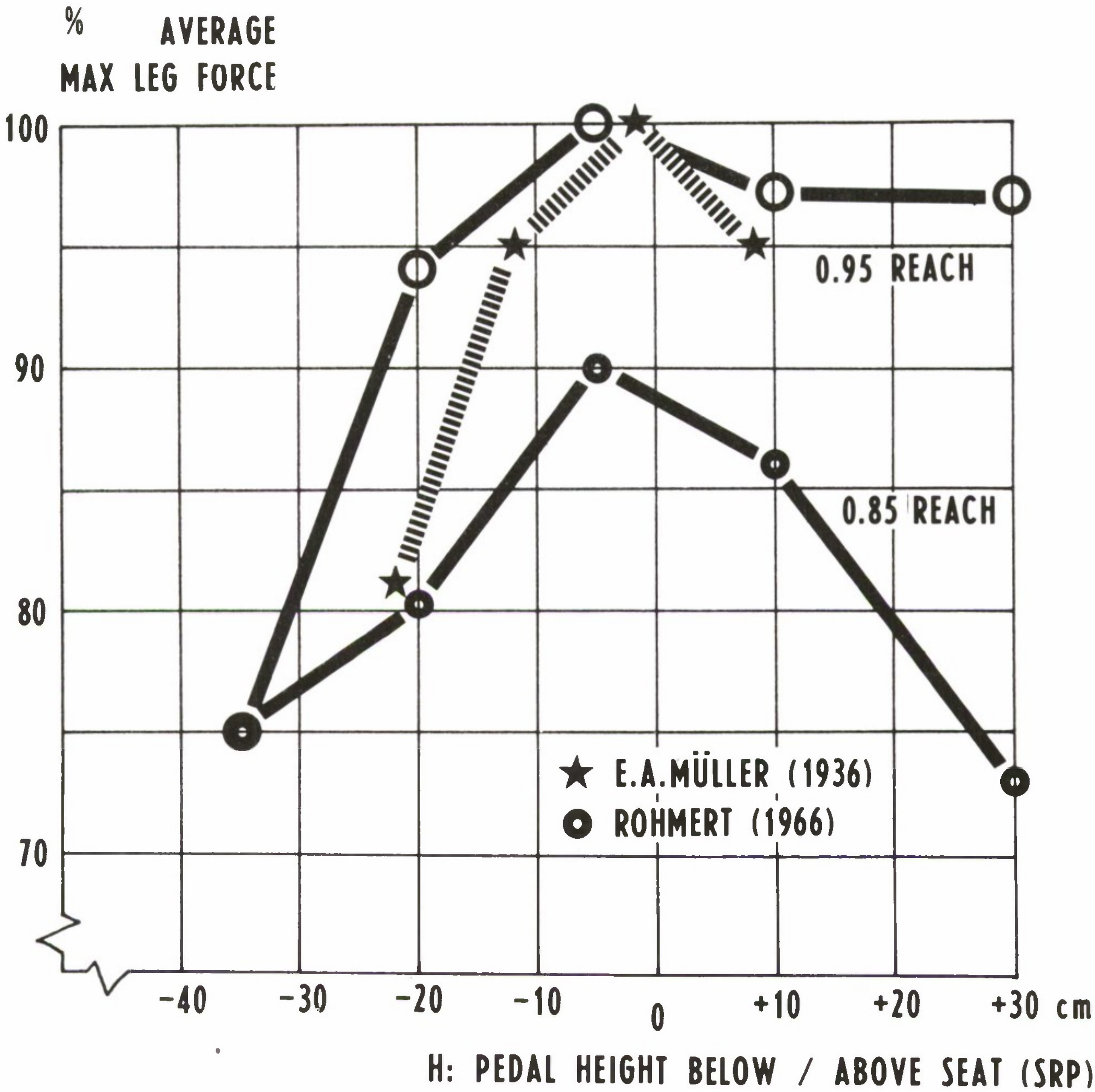


Figure 9. Leg Strength Depending on Pedal Height.

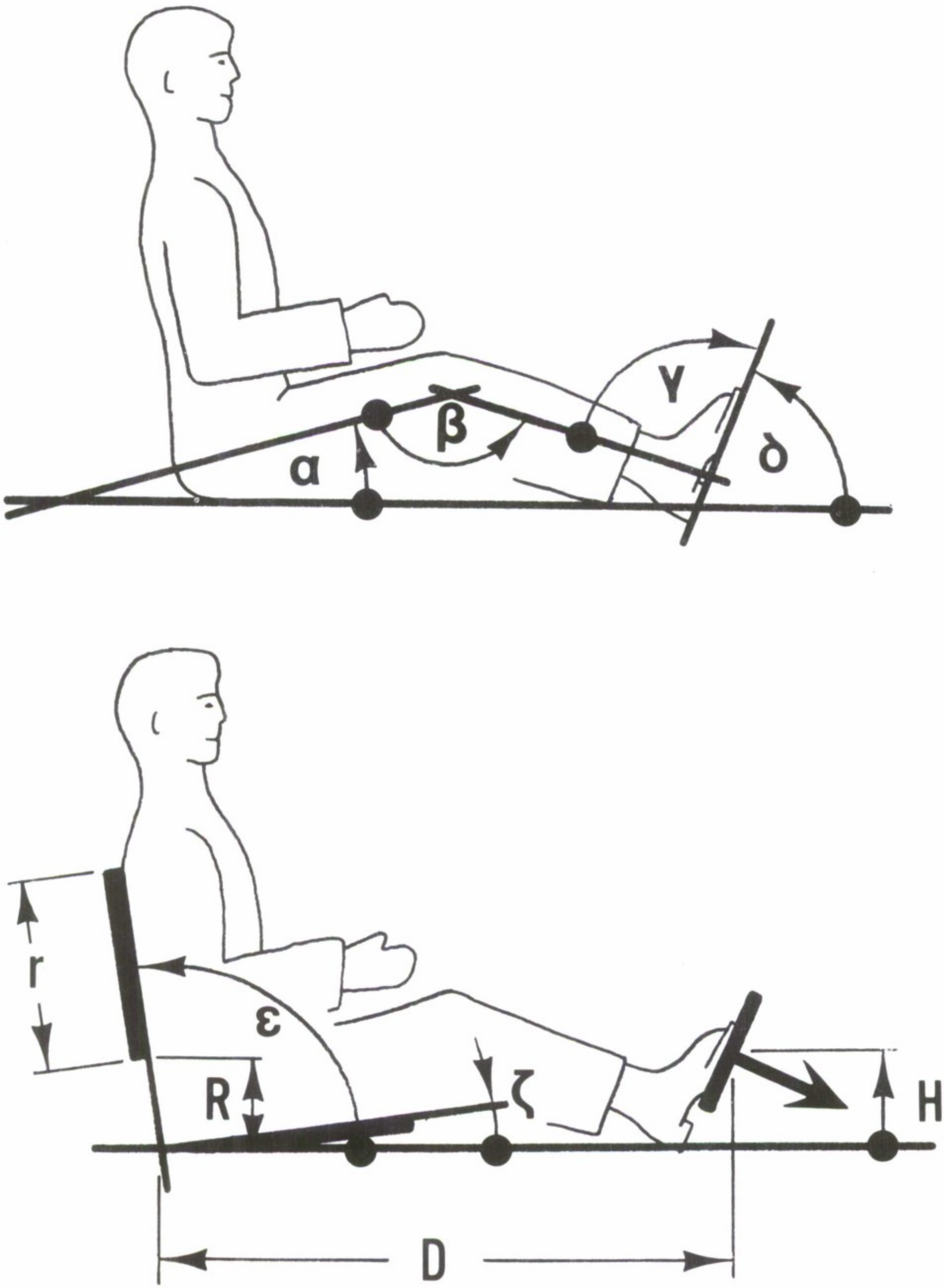


Figure 10. Variables Describing Body Posture and Body Support.

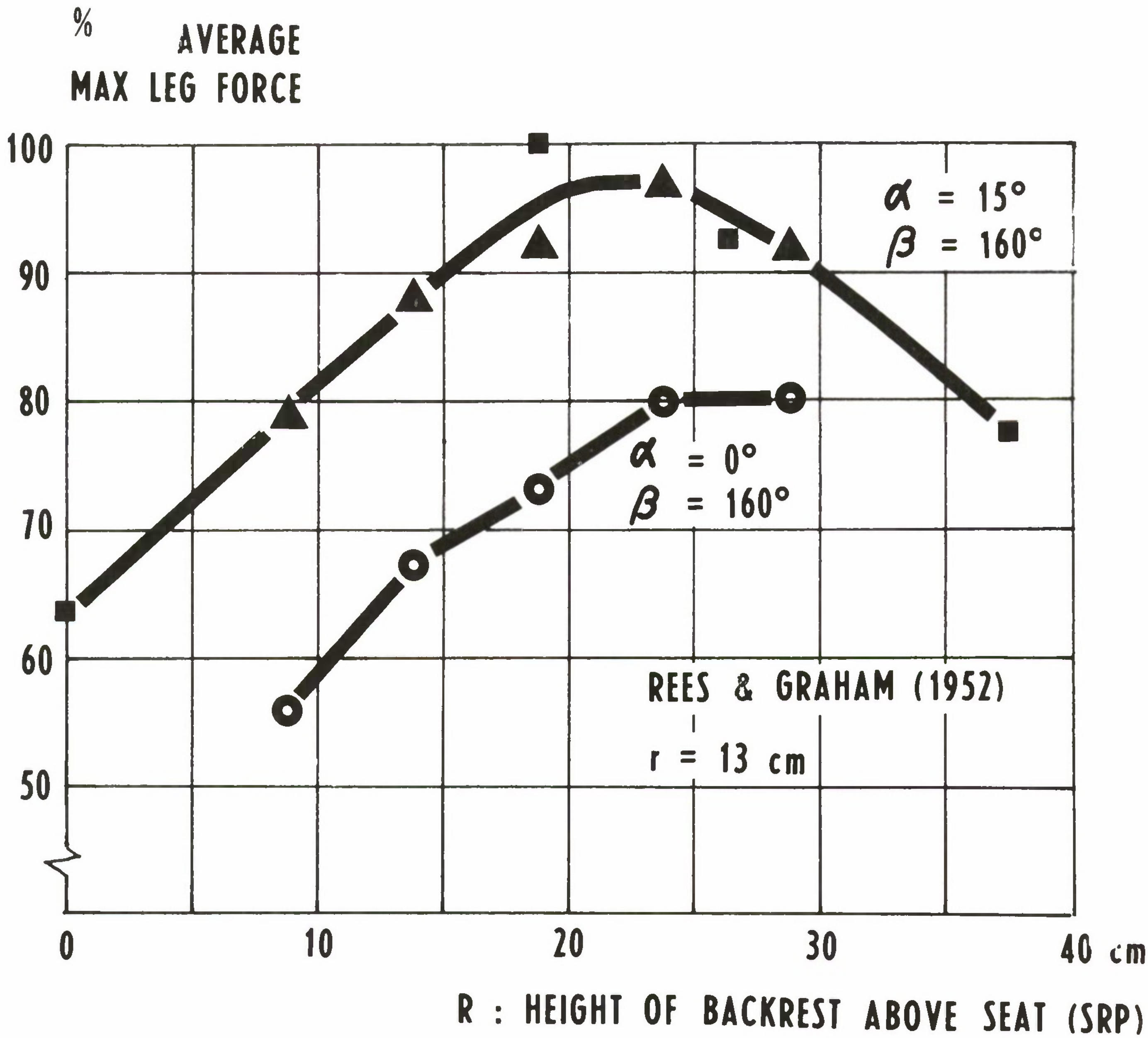


Figure 11. Leg Strength Depending on Backrest Height.

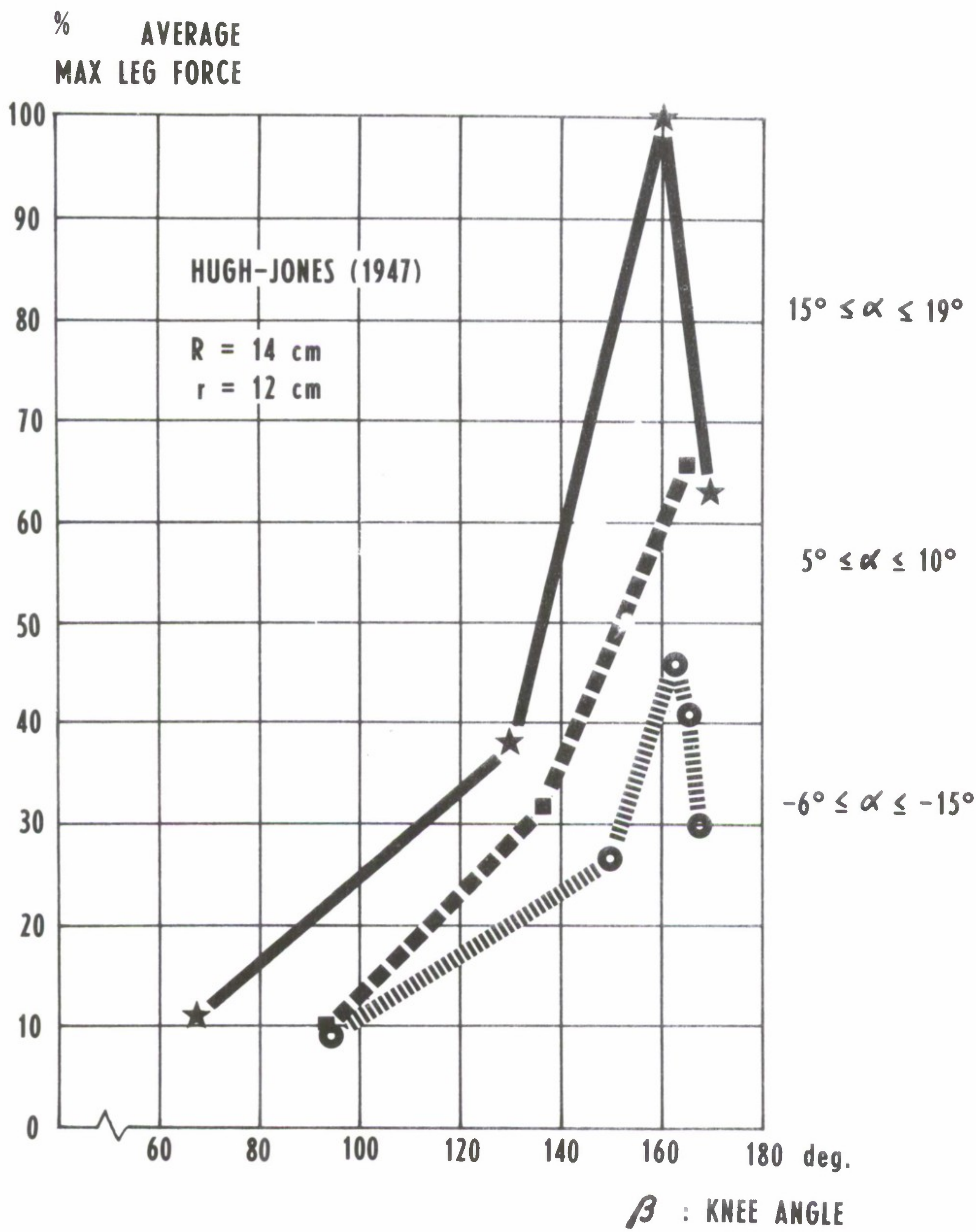


Figure 12. Leg Strength Depending on Knee Angle.

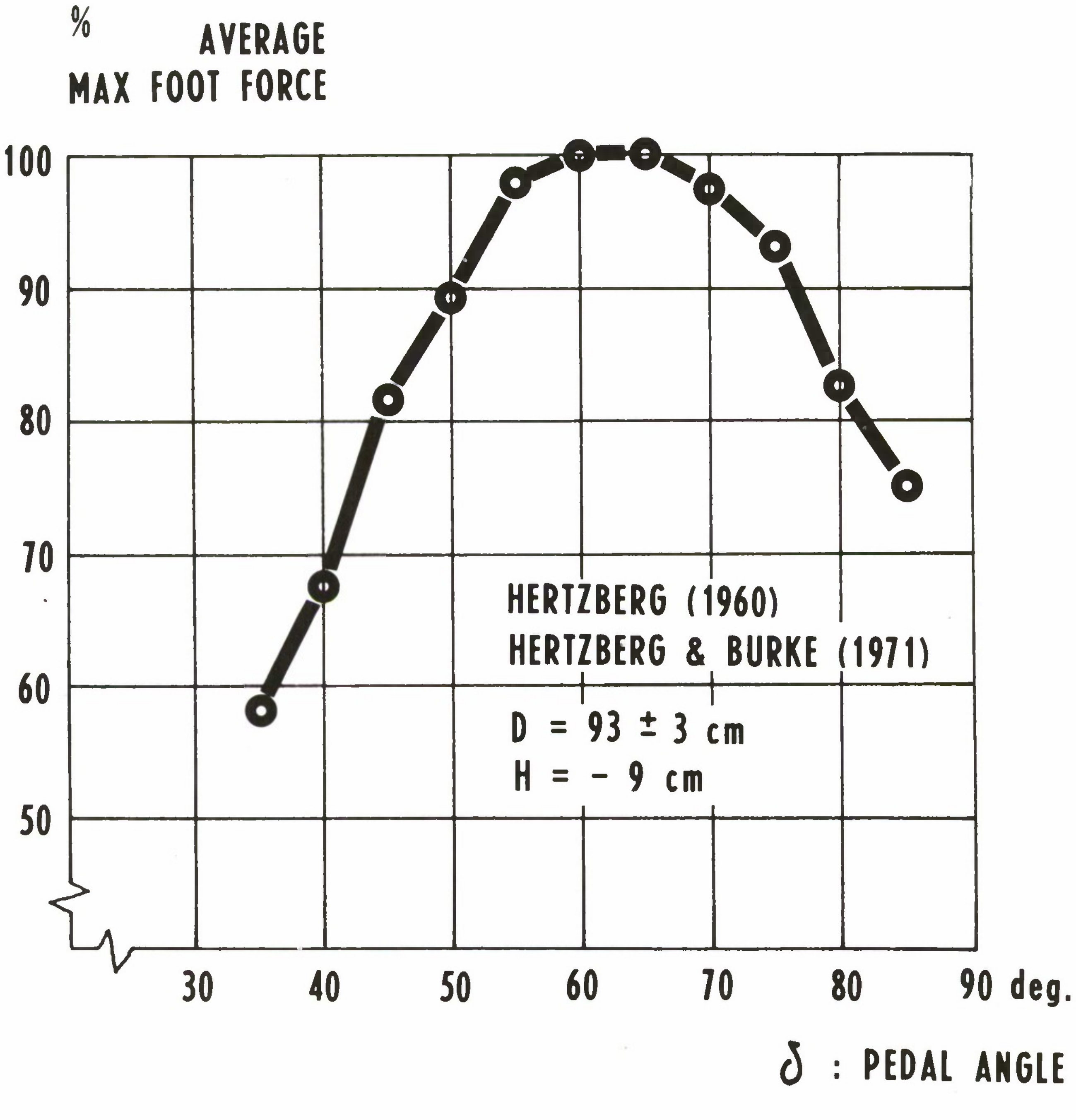


Figure 13. Foot Strength Depending on Pedal Angle.

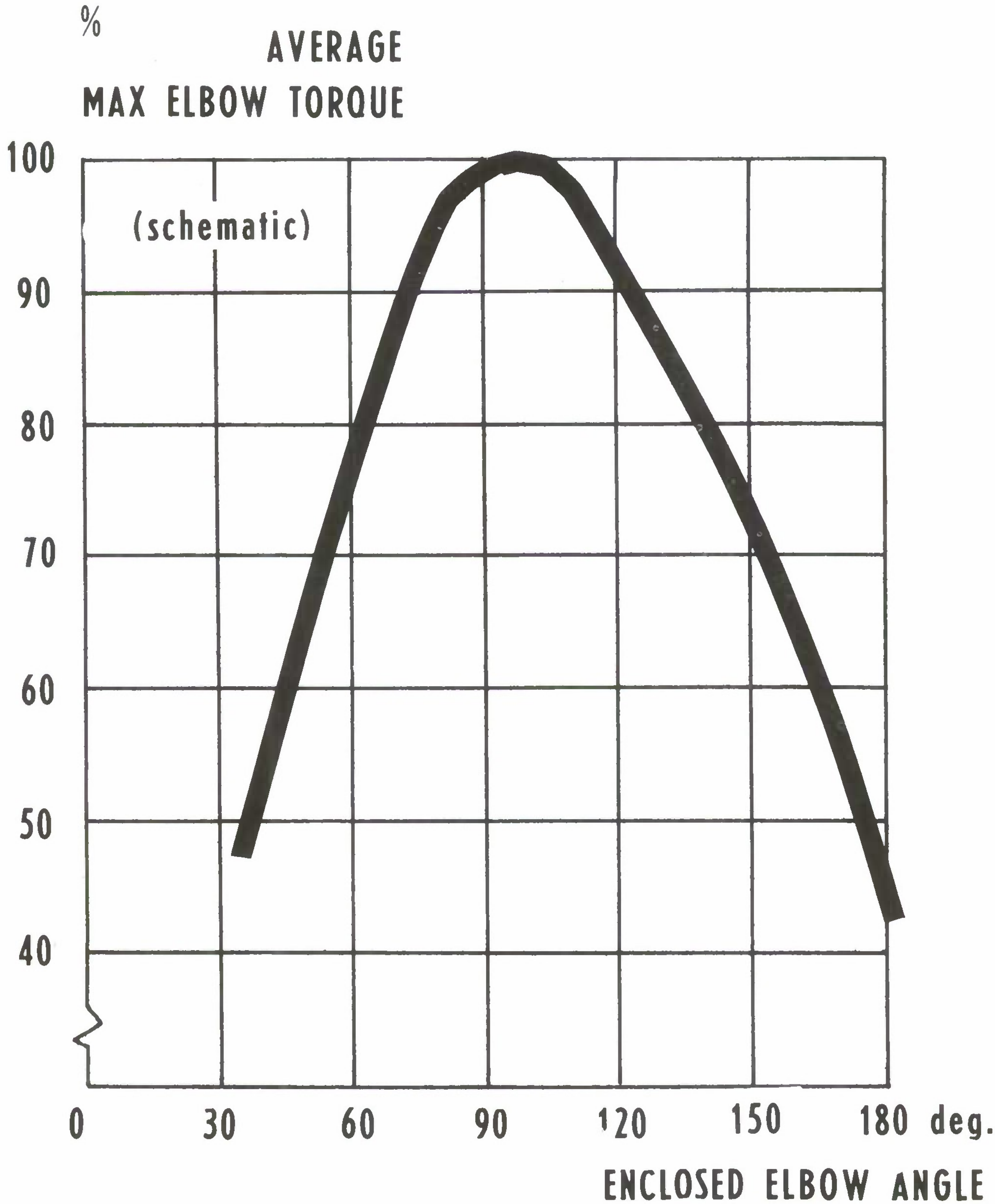


Figure 14. Elbow Torque Depending on Elbow Angle.

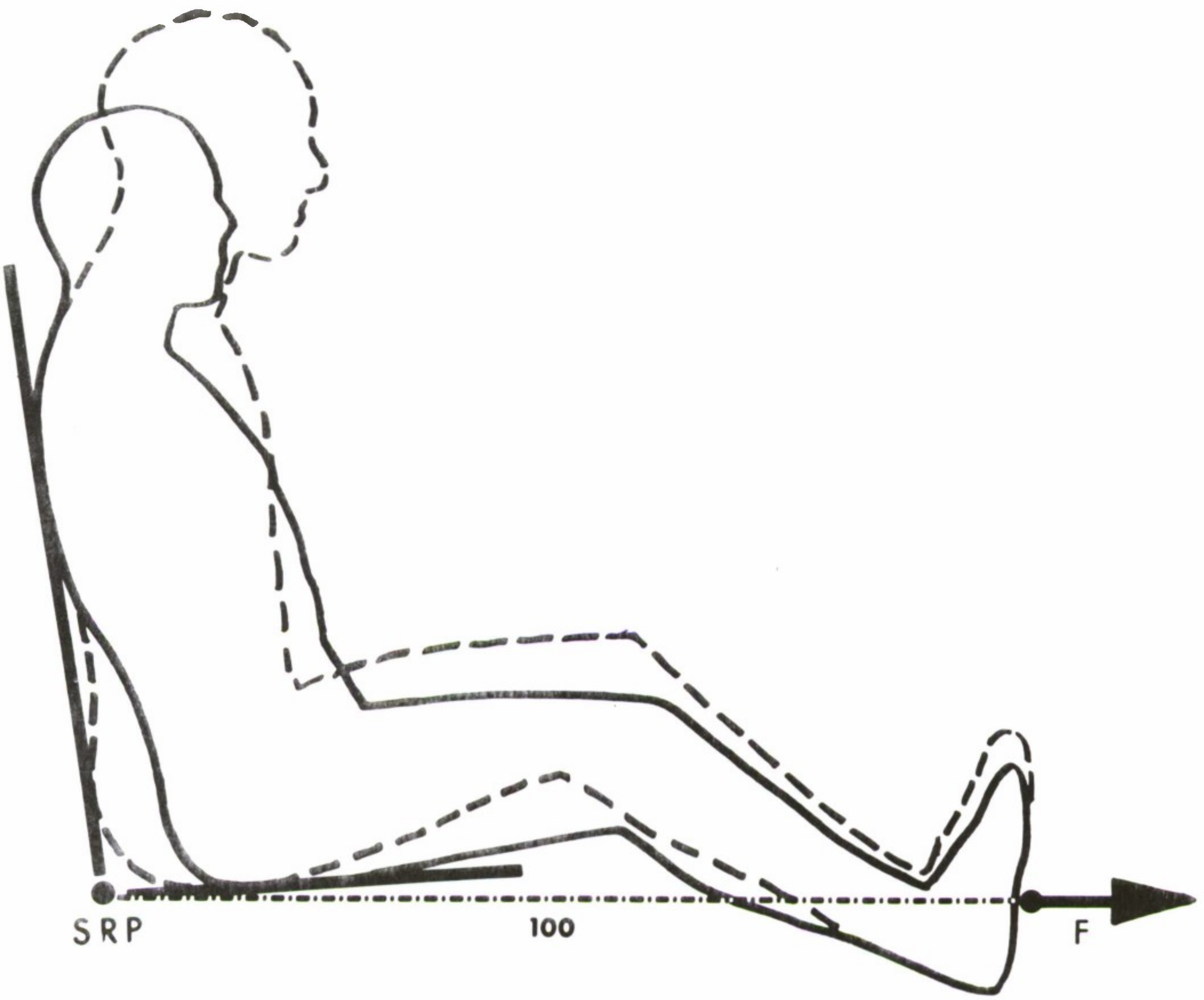


Figure 15. Body Positions of a Long and a Short Legged Operator Applying Force to a Pedal 100 cm in Front of SRP.

slide forward on the seat, consequently losing the firm support from the backrest, which in turn reduces their capability for strong leg thrusts on the pedal (anthropometric data from Garrett and Kennedy, 1971).

Figure 15 illustrates this condition. While the taller person exerts about the largest possible force at a knee angle of approximately 160° (see figure 12), the shorter operator attempting to reach the pedal has to move away from the seat below the lumbar region. Consequently, he receives supporting reaction force from the backrest at thorax height only which, according to Figure 11, reduces his leg strength exertable at the pedal by at least 25%.

Case 10

In an aircraft, an important emergency control was located 55 cm above, 28 cm to the right and 70 cm in front of SRP. These dimensions were chosen by the designer (about 20 years ago) so that the "average pilot"[5] could reach the control, with the elbow at an angle of approximately 120°, and activate it by applying an upward force of at least 300 Newton. During a test flight with a very small pilot at the controls, an emergency arose. Pulled back into the seat by the automatic safety harness, the pilot could hardly bring his hand to the emergency handle, which was at the periphery of his reach. With increased g_z-acceleration pulling his extended arm down, the pilot could not develop the muscular strength necessary to activate the emergency control. (Only exceptionally lucky circumstances prevented a serious accident.) Control location and force requirements have been changed since to avoid such incidences.

Figure 16 illustrates this case. While the tall pilot reaches the control comfortably, the small operator can hardly reach to the handle. Furthermore, while the taller operator, with an elbow angle of about 120°, can exert a rather large force F at the control (about 90% of his maximal strength; see figure 14), the small operator has to exert F with the arm extended, which reduces his strength capability to 50% or less of his maximum.

Case 11

Heavy American industrial machine tools have been delivered to India and are operated there by Indian personnel. Essential controls are arranged on the machines to be within reach of American workers. Indian operators, however, being generally of smaller size, have to stand on make-shift platforms or boxes to be able to reach some of these controls. Under this disadvantageous biomechanical condition, the Indian operators strain themselves much more than their American counterparts when applying the necessary forces and torques in working the controls (Sen, 1971)[6].

Figure 17 illustrates the conditions when the smaller worker has to operate a control located to be at eye height for a 50th percentile U. S. male. Reaching up with the arms almost extended reduces force capability and endurance, increases energy expenditure, and hence brings about unnecessary strain and fatigue (Astrand and Rodahl, 1970; Lehmann, 1961;

[5] *See Daniels (1952) for a discussion of the fallacy of the "average man" concept.*
[6] *Sen, R. N. Personal communications, 1971.*

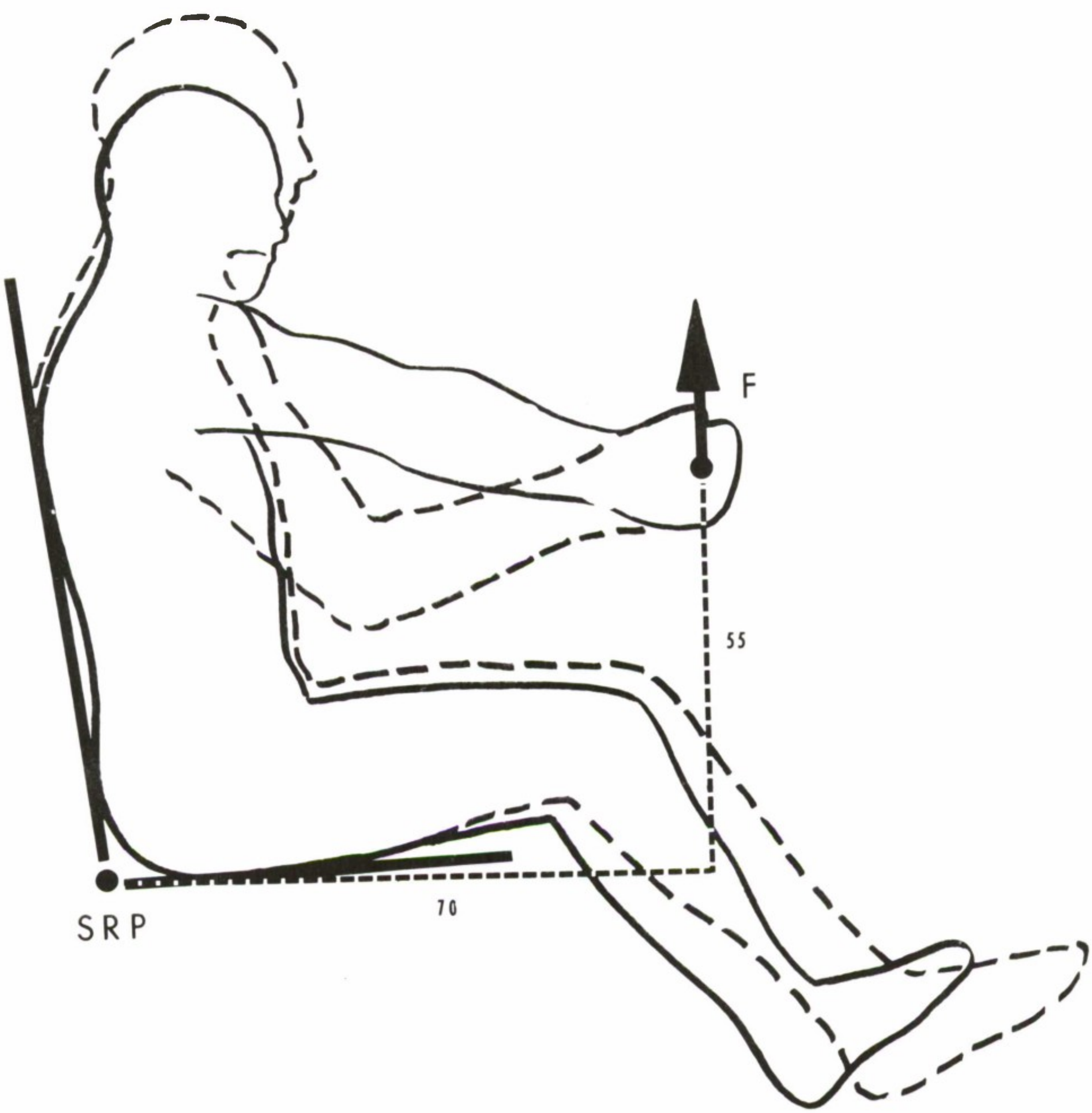


Figure 16. Arm Posture of a Tall and a Small Pilot While Applying an Upward Force to a Control Located 70 cm in Front and 55 cm Above SRP.

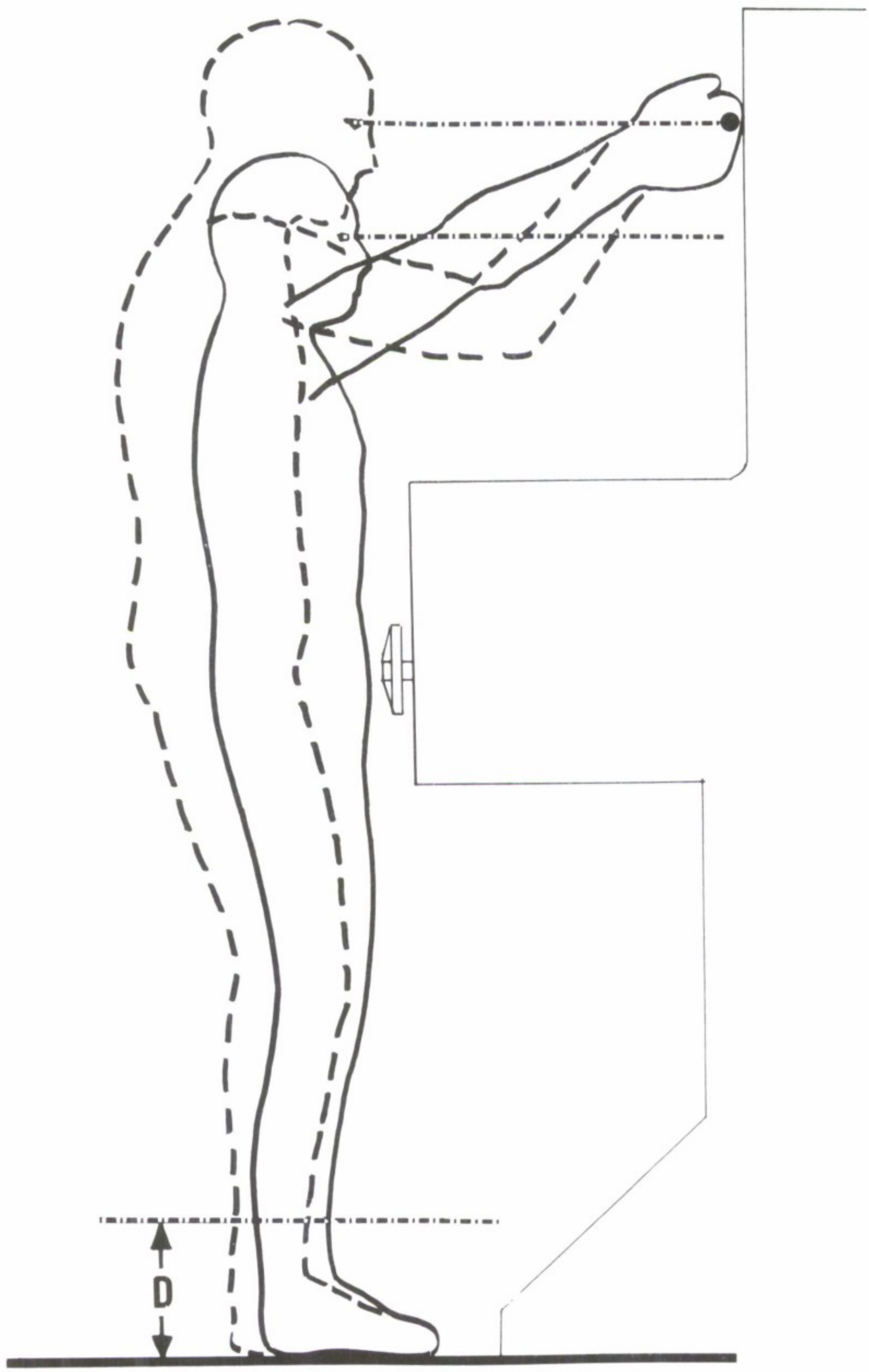


Figure 17. Body Posture of a Small Operator Using Heavy Industrial Machinery Designed for Taller Operators.

Scherrer, 1967). Elevating the standing surface by the distance D (about equivalent to the difference in eye height) facilitates operation of the high control, but also removes low controls from easy reach.

In each of the three cases cited, controls requiring muscular strength were located to suit a taller user population, and consequently were outside the normal reach of operators from smaller sized populations. Of course, the reverse also happens: Foot-operated controls in some automobiles designed for small-sized populations have been found to be too close to the seat, and spaced too close together, for drivers with longer legs and larger feet.

The solution for such design problems is to locate controls according to selected *ranges* of joint angles and lengths of body segments of user populations, instead of positioning controls at certain linear distances from reference points. When designing for ranges of body angles and segment lengths, operator strength available for control activation will vary relatively little between different populations since the biomechanical relationships (joint angles, lever arms, mechanical advantages, direction of g-stresses, etc.) remain similar. Figure 9 and figures 11 through 14 illustrate how, by designing for body positions, the strength available at the control can be kept at the maximum.

It must be acknowledged that design according to body positions and proportions, i.e., design to suit biomechanical principles, has been rather difficult in the past. The difficulties lay partly in the insufficient knowledge about biomechanical effects. In addition, it was very difficult to consider thoroughly the complex interactive biomechanical variables using tables of anthropometric and strength data and conventional design tools. Finally, some designers apparently did not have relevant information or did not bother to use it adequately.

Recent research in engineering anthropology and biomechanics (Reid, 1973) as well as in the development of computerized biomechanical man-models promises fast and easy access to such information, and facilitates its use in the design process (Kroemer, 1972). The Universities of Cincinnati, Florida and Michigan, the Boeing Company, the Aerospace Medical Research Laboratory in the U.S.A., and the University of Nottingham in the UK (to name only a few) are actively developing computer models of the man-workplace geometry which enable the designer to use a computer terminal as an "advanced drawing board" to fit new equipment to man's dimensions and biomechanical characteristics.

SECTION V

PROCEDURES IN DESIGNING FOR OPERATOR STRENGTH

Using several examples and case reports, a number of theoretical aspects of strength have been pointed out in the previous sections.[7]

- Static strength is the result of a maximal, voluntary, isometric, muscular effort.
- Strength reflects not only the operator's muscular capabilities, but also depends on body posture and support, and on motivational and environmental conditions.
- Strength is a biomechanical variable, intimately related to the anthropometry of the operator and to the geometry of the workplace.
- Strength is specific to the location of the point of application, and to the nature and direction of the effort.
- Most strength scores are, even for the same subject, neither highly correlated with other measurements of strength, nor with anthropometric dimensions.
- Operational strength is closely related to lateral preferences of the operator, and to his stereotypical "control action/equipment response" patterns.
- Strength scores represent maximal values which, under operational conditions, should not be required. Instead, normal control activation requirements must not exceed a defined portion of the total strength.

Compilations of strength data of different populations are very incomplete, and international surveys to secure comparable information are urgently needed. However, using the data available, design procedures and rules have been developed which enable the Human Factors engineer to design equipment according to the strength characteristics of different operator populations. An advanced concept of this procedure is the use of computerized man-models (Kroemer, 1972). In principle, the ergonomic design regimen is as follows:

Phase 1: Establish the critical anthropometric dimensions of the prospective user populations.

Phase 2: Establish operational (minimal and maximal) reach envelopes for each distinct operator sample.

Phase 3: Establish whether equipment worn, environmental or other conditions can affect operator mobility and strength.

Phase 4: Select those spaces for possible control locations in which the areas of convenient reach of all user groups overlap. If no such areas exist, establish which adjustments in control location and/or seat or standing platform are necessary to achieve overlapping of reach spaces. If no such adjustments can be made with reasonable effort, separate designs are unavoidable to suit different operator populations.

Phase 5: Simultaneously

- establish operator strength capabilities in the selected reach areas. Consider carefully the operational conditions and select preferable types of strength.

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[7] *See also the appendix.*

- establish system requirements in terms of control force/torque vectors (location, direction, magnitude). Consider alternate solutions.

Phase 6: Match operator capabilities and system requirements. Considerations generally required in this phase are:

Select such a body posture and provide the operator with such support that his body members are in comfortable, biomechanically advantageous positions. If the operator has to stand while working manually, his upper arms should be normally vertical or slightly elevated, and the elbow angle should be near 90 degrees. A sitting position is often preferable, in fact necessary if controls must be frequently and/or continuously worked with the feet. For the exertion of rather large forward forces exerted on pedals, the operator's legs should be nearly extended. For smaller force requirements, the knee angle can be between 150 and 100 degrees. The best arm position for the seated operator is the same as for the standing worker. (For further detailed information, see Human Engineering/ Ergonomics Handbooks). Biomechanically advantageous ranges of body segment positions determine, in combination with anthropometric dimensions, the location, type, and operation of controls that require strength inputs from the operator.

Phase 7: If a conflict arises in Phase 6, determine whether critical control force requirements are set by system requirements, or by operator characteristics.

- System requirements are usually either at a very low level, or at an extremely high level. A low level allows even very weak persons to operate the equipment. (An example is easily operated handles of emergency doors in schools). A high level will cut off a large portion of prospective operators, who cannot exert such strength. (Occasionally, such high requirements are set purposely to exclude certain undesired operator groups: e.g., small children who should not be able to open automobile doors). If the system requirement is exceedingly high, it must be lowered by redesigning the system. Possible means are to include power boosters (power steering, fly-by-wire, etc.), or to change the mechanical advantages by using different controls, or by rearranging the controls within the operator's workspace.

- Operator strength values determine control characteristics according to what the designer considers to be "optimal" (tolerable, permissible, reasonable, desirable, etc) along the scale of 0 to 100% strength of the prospective operator. This optimal point (design strength value) is most conveniently expressed as a percentile value of operator strength.

  Less than 20% of total strength can be maintained over practically indefinite periods of time without deterioration due to fatigue. This 20th percentile is hence one of the most important cutoff values in design for strength, if the effort has to be maintained for longer periods of time.

  Very often the Human Factors engineer has to exclude as well the extremely weak as the extraordinarily strong operators from his design considerations. For this purpose, percentile ranges have proven to be very useful.

In most military services, for example, the 5th (or 3rd) percentile is used for lower limits,

and the 95th (or 98th) percentile constitutes the upper boundary. Within these limits, 90% (or 95%, respectively) of the total data population is included. Using regular statistics, applied to a normally distributed data collective, percentile values p can be calculated easily from the mean (X) and standard deviation (SD) according to $p = X \pm a\ SD$. Selected values for factor "a" are listed in table 3.

Table 3: Values for Factor "a" to Calculate Selected Percentiles

Factor "a"	Percentile
2.33	1st, 99th
1.88	3rd, 97th
1.65	5th, 95th
1.28	10th, 90th
0.84	20th, 80th
0.65	25th, 75th
0	50th (mean)

Increasing the design range to include a larger portion of the data population is often desirable, but can become quite costly. Doubling, for instance, any of the smaller values for "a" from table 1 shows that distinctly less than double as large a percentile range is included in the new limits. This disproportion becomes very pronounced if the cutoff values are located at the extremes (in the areas of the small and large percentile numbers.) Two objectives oppose each other: to include as large a data population as possible and, at the same time, to keep construction cost and equipment bulk as small as feasible. The ergonomist has to decide where to compromise.

The procedures described in Phases 1 through 7 apply primarily to new equipment which must be designed according to the biomechanical characteristics of different operator samples. However, the regimen also covers the case that existing equipment must be checked (and modified, if necessary) for its suitability of a new operator population. Figure 18 illustrates this case.

An existing cockpit, designed to fit a US population, was considered to be used by (a) Japanese operators, whose legs are shorter, but whose trunk dimensions are similar, or by (b) Vietnamese operators whose dimensions are generally smaller than comparable US measures (Kennedy, 1972). Here, the arrangement of controls was of major concern, since previously difficulties in meeting control force requirements had been reported. Assuming that the seat was to be maintained, it became evident that difficulties in control operation could exist at the forward reach area (1), at the major manipulation area in front of the trunk above the thighs (2), and at the pedals (3).

For control operation in area 1, mainly small forces and torques were required, most of which could be applied while the operator leaned slightly forward. Consequently, no serious difficulties were to be expected.

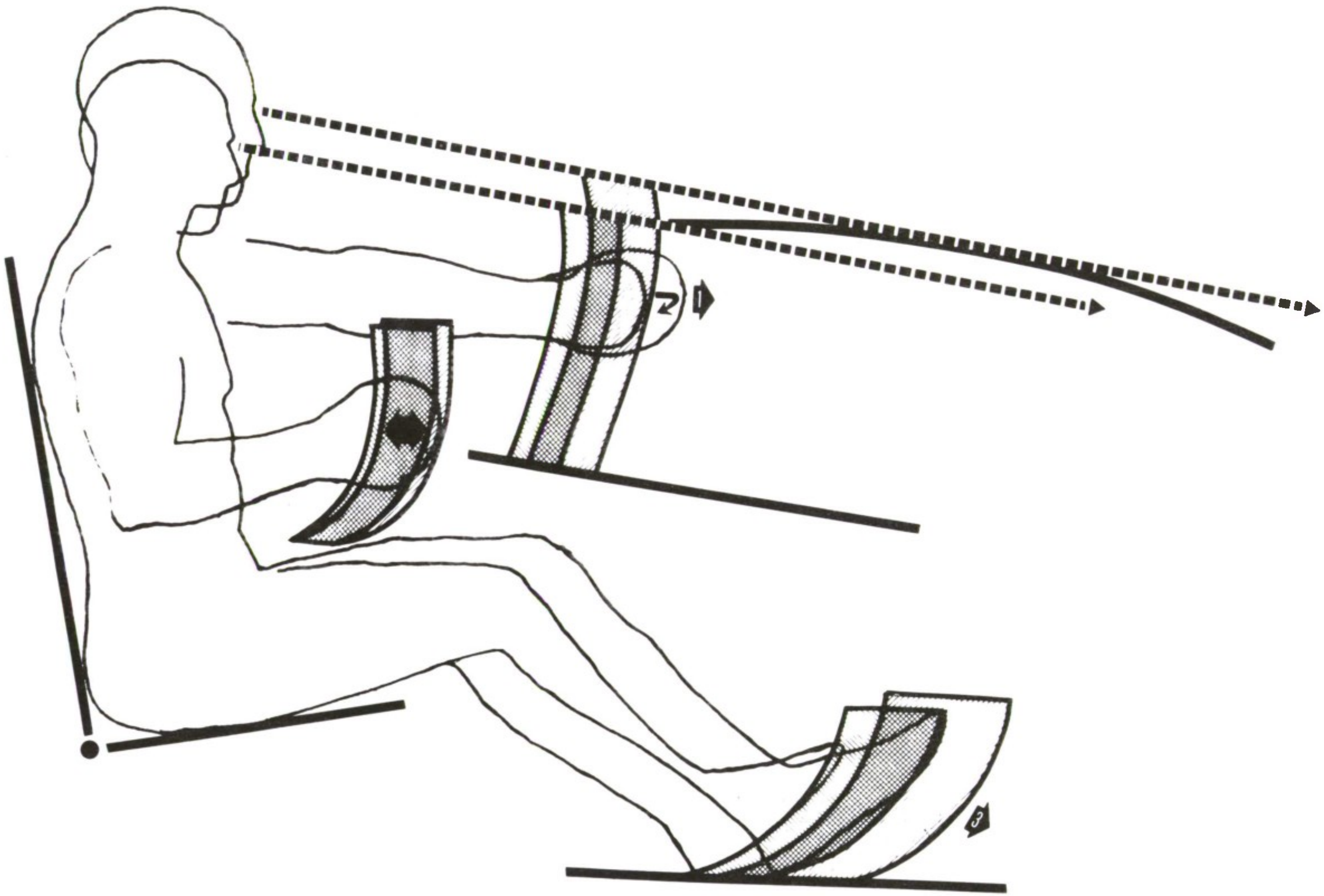

Figure 18. Areas for the Location of Hand and Foot Operated Controls for Different User Populations.

In control area 2, in front of the trunk and above the thighs, a major control (stick) is located. Evaluation of anthropometric dimensions showed that the stick control could be slightly lower (about 3 cm) and also moved aft (7 or 8 cm) for either Asian operator population. However, assessing the effects of such relocation on strength capabilities of the operator did not show significant changes in strength under operational conditions. Hence, relocation of the control was deemed desirable, but not mandatory.

In area 3, pedals are located which are essential for systems operation. Both Asian populations could not reach the pedals sufficiently to operate them securely throughout the range, as the relatively small area of overlapping reach envelopes indicates. Since application of up to 800 or 1000 Newton with the pedals fully moved forward can be necessary, relocation of the pedals by moving them backwards by 10 to 12 cm was found to be mandatory.

In this example, strength and anthropometric data had to be taken from tables compiling this information, and had to be superimposed on the cockpit drawings. Verification of the conclusions was obtained in field tests. Computerized biomechanical man-cockpit models, currently being developed, will significantly facilitate the design of workplaces and equipment to be adapted specifically to anthropometry and strength capabilities of different user populations.

SECTION VI

CONCLUSIONS

Strength has been defined as the maximal force muscles can exert in a single voluntary effort. Since strength cannot easily be assessed at the living muscle in situ, it is traditionally measured as the force or torque available at the interface with the measuring device. This is indeed the information which the Human Factors engineer needs for controls that must be activated forcefully by the human operator.

Strength data as well as ergonomic design tasks are highly specific, since neither a "general strength" exists nor a "universal design." Control parameters like location, type, and directional requirements relate to biomechanical factors which, in turn, determine the operator strength available.

The strength exerted by a subject depends not only on his muscular capability, but also on a number of experimental (technical, motivational, physiological, biomechanical environmental) variables. Hence, standardization of strength testing methods is highly desirable in order to arrive at reliable and comparable data needed for the design of tools, equipment, and complex man-machine systems.

Strength available for control operation is critical in setting either minimum force/torque levels, so that even the weak operator can manipulate the controls, or in selecting maximal limits to prevent accidental actuation or damage by too strong an operator. Along the scale of minimal to maximal strength of the operator population, the designer selects an "optimal" value for control operation under normal conditions. Percentile values and ranges have been found to be convenient and accurate in describing the data sample, and in selecting design values.

Control location is another critical aspect in designing for the human operator. The workspace available for controls depends primarily on body dimension and body position. Within the total reach envelope of the hands and feet, certain locations allow very effective use of muscular strength, while other control locations are much less suitable.

Handedness can also be a decisive factor in control design. Lateral preference must be described in terms of the efficiency of performing tasks with either side of the body. Laterability intermingles with stereotypical patterns of the operator population in terms of control operation and expected response of the plant. Such patterns have been shown to vary even between rather closely related populations. Anecdotical evidence suggests that larger stereotypical discrepancies exist between populations with rather distinct histories and customs.

The biomechanical principles of the human body are the same for all populations. Hence, design for selected ranges of dimensions of joint angles, and of body positions applies to all

user populations. Such a design procedure has been difficult in the past, primarily for technical reasons. However, new concepts of geometry, biomechanics and ergonomics in computerized man-machine-models promise to provide very efficient design tools for the ergonomist.

For many types of control operations, information on static force/torque capacities of the prospective user population yields indispensible data for control design. Isometric strength data are characteristic of the capacity for short-time maximal efforts, and the ability to maintain submaximal strength over given periods of time. Strength data are important in designing for user populations different in cultural and national traits as they pertain to physical health and training, dexterity and stereotypical patterns, and to anthropometric characteristics.

APPENDIX

ERGONOMIC ASPECTS OF STRENGTH

STRENGTH TERMINOLOGY

"Strength is the maximal force muscles can exert isometrically in a single voluntary effort." (Kroemer, 1970a)

In the past, some confusion has resulted from uncritical and careless use of terms in connection with muscular efforts. A discussion of related terminology and of past discrepancies in physical and physiological concepts has been carried on in the literature (Brunnstrom, 1966; Koopman cit. by Burger et al., 1967; Elftman, 1966; Kroemer, 1970a; Purswell, 1967; Ramsey, 1968; Starr, 1951; Whitney, 1958). In accordance with the definition of strength given above, such terms as work, power, dynamic or the often misused isotonic do not apply to the *isometric-static, maximal, short-time muscular effort* to exert force or torque on a measuring device.

BIOMECHANICAL ASPECTS OF STRENGTH

Since it is very difficult to assess strength at the muscle in vivo et situ, strength traditionally has been measured as the force (or torque) applicable to an outside object, i.e., the measuring device. This external result of internal muscle tension is of primary interest to the designer. He must concern himself with internal processes only insofar as they affect the strength available at the control interface.

Human strength is measured as a vector, i.e., defined in magnitude and direction. Its location is best referenced to the joints of the operator's body.

Strength is a function of time: It is (mainly for physiological reasons) assessed as the vector exerted during a period of less than 8 seconds, often during 2 to 5 seconds. Finally, strength is assessed statically, when acting and reacting forces are in balance and no motion occurs between the operator's body and the testing device.

PHYSIOLOGICAL ASPECTS OF STRENGTH

Excellent articles by Hoyle, 1970; Peachey, 1968; Stern, 1971; Tricker and Tricker, 1966, can serve as introductions to the anatomy, biomechanics and physiology of muscular action. Muscles involved in maximal isometric contractions sustained for more than 8 to 10 seconds become fatigued, mainly due to anoxia and accumulation of metabolites (for reviews, see Astrand and Rodahl, 1970; Lehmann, 1961; Lind and McNicol, 1967; Müller, 1970; Scherrer, 1967). Such fatigue reduces the magnitude of strength that can be exerted. A number of researchers (among the first were Monod, 1956; Rohmert, 1960; Caldwell, 1963; and Molbech, 1963) demonstrated a nonlinear relationship between the fraction of total strength required,

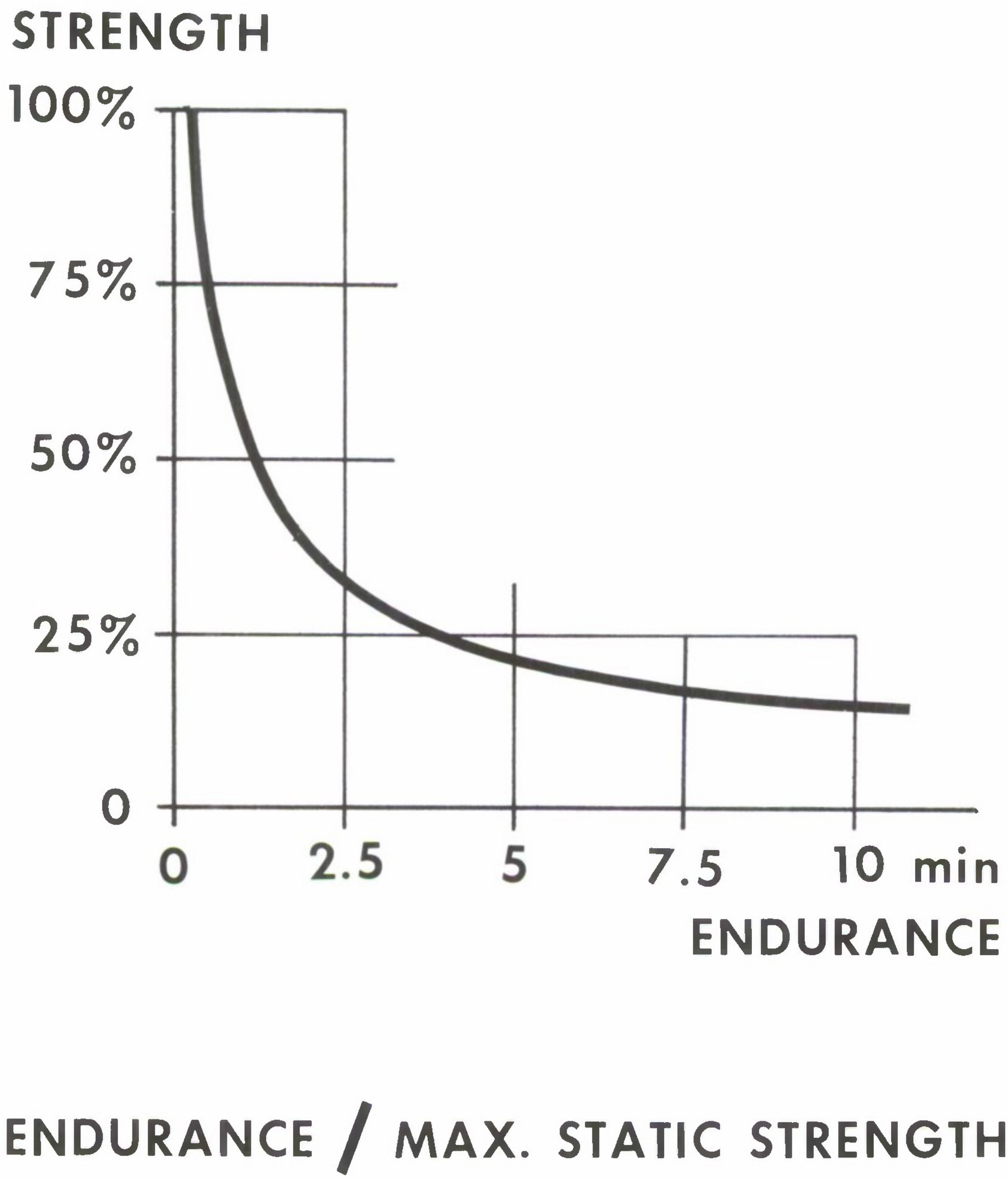

Figure 19. Endurance Time as a Function of Partial Strength Requirement. (Schematically after Monod, 1956; Rohmert, 1960; Caldwell, 1963; Molbech, 1963).

and the period of time during which this fractional strength can be maintained. Figure 19 depicts this relationship schematically.

Physiologically as well as physically it matters very much whether muscular force is exerted while the resisting object (measuring device or control) stays stationary, or whether relative displacement occurs between subject and object. Traditionally, "strength" is being measured in the stationary (static, isometric) condition. The fact that dynamics are excluded in the assessment of strength has far reaching consequences discussed elsewhere (Kroemer, 1970a). It may suffice here to repeat that it is questionable how much (if any) predictive value static, short-time maximal strength has with respect to (a) dynamic work capacity, and (b) submaximal efforts.

CORRELATIONS AMONG MEASURES OF STRENGTH AND ANTHROPOMETRIC DATA

One would expect measures of strength (e.g., as exerted with arm and leg) to be highly correlated. Unfortunately, this is generally not the case. A number of recent studies have shown that while many (but not all) measures of strength correlate positively with each other and with anthropometric data, the correlations are too low to have much predictive value for the designer (Laubach, 1969; Laubach, Kroemer and Thordsen, 1972; Laubach and McConville, 1966, 1969; Whitley and Allan, 1971). The demonstrated specificity of strength scores implies that strength scores preferably should be measured individually and not be calculated from regression equations and correlation factors.

METHODOLOGICAL ASPECTS OF STRENGTH MEASUREMENTS

The amount (and direction) of strength measured depends not only on the subject's pyhsiological (especially muscular) capacity, but also on the testing device used and on body posture and body support of the subject. In addition to these biomechanical factors, the subject's familiarity with test equipment and procedures, his skill of generating strength, and the training status of his muscles can also affect the outcome of the test. Motivational factors sometimes have been neglected in strength testing: Table 4 lists several categories of motivational factors, and their probable effects on the magnitude of strength attributed to the subject.

Subjective interpretation and statistical treatment of the experimental data have also been shown to be a possible source of variations in strength scores. A discussion of methodological details has been pursued in the literature (see, e.g., Ayoub and McDaniel, 1971; Kroemer, 1970a; Roebuck, Kroemer and Thomson, to be published). A checklist has been prepared by Kroemer and Howard (1970a) to assist in recognizing possible sources of variations in strength testing, and in standardization of testing procedures.

Standardization of at least some key measures is as important in strength testing as in anthropometry (Hertzberg, 1968) in order to secure comparable data. Hence, early in 1972,

Table 4. Variables Likely to Affect Motivation and Hence Strength Measurements

Variables Affecting the Subject	Likely Effect on Muscular Strength
Feedback of results	+
Instruction on how to exert	+
Arousel of ego involvement, aspiration	+
Pharmaceutical agents	+
Startling noise, subject's outcry	+
Hypnotic over-riding of inhibitors	+
Setting of goals, incentives	+ (−)
Competition, contest	+ (−)
Verbal encouragement	+ (−)
Fear of injuries	−
Spectators	?
Deception	?

an Ad-Hoc Work Group for Standardization of Muscle Strength Testing was established by a group of interested individuals.* Their consensus was that the effort to standardize should be initially limited to the assessment of static (isometric) strength. The recommendations for static strength testing procedures, developed by the Ad-Hoc Group, follow largely the proposals by Kroemer (1970a) and Kroemer and Howard (1970a) and were first publicly reported at the Annual Conference of the Americal Industrial Hygiene Association in Boston, MA, May 1973. They are as follows:

DEFINITION:
STATIC STRENGTH IS THE CAPACITY TO PRODUCE TORQUE OR FORCE BY A MAXIMAL VOLUNTARY ISOMETRIC MUSCULAR EXERTION. STRENGTH HAS VECTOR QUALITIES AND THEREFORE SHOULD BE DESCRIBED BY MAGNITUDE AND DIRECTION.

1. Static strength is measured according to the following conditions:
   a. Static strength is assessed during a steady exertion sustained for four seconds.
   b. The transient periods of about one second each, before and after the steady exertion, are disregarded.
   c. The strength datum is the mean score recorded during the first three seconds of the steady exertion.
2. a. The subject should be informed about the test purpose and procedures.
   b. Instructions to the subject should be kept factual and not include emotional appeals.
   c. The subject should be instructed to "increase to maximum exertion (without jerk) in about one second and maintain this effort during a four second count."

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d. Inform the subject during the test session about his general performance in qualitative, non-comparative, positive terms. Do not give instantaneous feedback during the exertion.
e. Rewards, goal setting, competition, spectators, fear, noise, etc. can affect the subject's motivation and performance and, therefore, should be avoided.

3. The minimum rest period between related efforts should be two minutes.
4. Describe the conditions existing during strength testing:
   a. Body parts and muscles chiefly used
   b. Body position
   c. Body support/reaction force available
   d. Coupling of the subject to the measuring device (to describe location of the strength vector)
   e. Strength measuring and recording device
5. Subject description:
   a. Population and sample selection
   b. Current health status (medical examination/questionnaire is recommended)
   c. Sex
   d. Age
   e. Anthropometry (at least height and weight)
   f. Training related to the strength testing
6. Data reporting:
   a. Mean (median, mode)
   b. Standard deviation
   c. Skewness
   d. Minimum and maximum values
   e. Sample size

COMMENTS

Re Definition

The wording advisedly allows assessment of static strength either of a given muscle *in situ*, or as the externally measured result of the contraction of one muscle or a group of muscles acting at given mechanical advantages.

Re 1

The theoretical basis for an "isometric exertion" is that the contracting muscle(s) neither lengthen(s) or shorten(s) appreciably. This excluson of motion facilitates standardization. Maintaining a muscle contraction at a maximal level without change in body position over a definite but limited period of time is the most practical technique to achieve an isometric exertion.

Striving for a constant exertion period of four seconds assures that the required three seconds are indeed available. This sampling period of three seconds for the calculation of the mean score appears to be sufficient to check on the steadiness of the exertion. During the sampling

period strength variations within ±10 percent of the mean score should be tolerable.

Another popular technique of assessing strength is to have the subject exert a sudden peak force in a jerking effort. This method invites nonisometric (dynamic) muscle contraction often accompanied by storage and/or release of energy in moving body parts.

Re 2
A subject's ability and willingness to fully exploit his inherent muscular strength capabilities can be significantly affected by the experimenter and/or by the experimental conditions; however, the effects are often unpredictable. Hence, in the interest of standardization, it is preferable to keep the experimenter's instructions factual and the experimental conditions neutral.

Re 4
Strength exerted depends not only on muscular capabilities, but also and to a large extent on the prevailing biomechanical advantages, such as direction of the strength vector, relative angular locations of the body segments involved, their link lengths, body support, etc. Only in a few cases (like in measurements of grip strength) are these conditions *eo ipso* defined and require no detailed description. Usually, a model of the body showing segment position during the strength exertion must be carefully conveyed to the reader so that he can understand the experimental conditions and use the data. If strength is reported as a torque, the lever arm (moment arm) and locations of the axis of (attempted) rotation need to be reported. If strength is reported as a force, the direction and location of the vector need to be carefully reported, generally with respect to the body segment transmitting the strength. The results of scientific investigations, including strength measurements, are useful only if they are so completely described that they can be repeated.

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